MUSCLE FORCE STEADINESS AND ACCURACY IN OLDER ADULTS WHO HAVE FALLEN: EXPLORING THEIR ABILITY TO CHANGE AND ANY LINKS TO MOBILITY

by

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STATEMENT OF DISSERTATION APPROVAL

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ABSTRACT

Older adults experience age-related challenges including muscle weakness, impaired mobility, and increased fall risk. Further, controlling submaximal muscle forces may also be impaired, particularly with eccentric (ECC) contractions, as they demonstrate greater variability in maintaining steady and accurate force output, characterized as muscle force steadiness (MFS) and muscle force accuracy (MFA). Moreover, reported evidence of MFS, and functional mobility in older adults who have fallen is very limited.

The primary and secondary aims of this dissertation were to compare whether repeated bouts of concentric (CON) and ECC contractions of the knee extensors improves MFS in healthy young (HYA), old (HOA) and older adults who have fallen (OIA), and whether MFS differs between the groups. The tertiary aim was to examine relationships between MFS, MFA and four functional mobility tests (FMT). An exploratory aim was to compare whether resistance training (RT), either traditional or negative eccentric work, improves MFS in OIA in a falls reduction program. Three groups, HYA (age 18-30), HOA (≥65) and OIA (≥65, two or more co-morbid conditions), were recruited. Maximal voluntary isometric contractions (MVIC) were performed. A submaximal target force (50% MVIC) was used when measuring MFS and MFA. The OIA group then performed four FMT, and participated in 12 weeks of RT. Each group demonstrated early improvements in MFS with repeated bouts and obtained stable measures within six to nine trials. The OIA group exhibited greater force variability for both CON and ECC contractions compared to HOA and HYA. HOA exhibited greater force variability for only CON contractions compared to HYA. No significant associations were seen between MFS and FMT. However, MFA and FMT were significantly correlated with moderate to strong associations for only ECC contractions. Twelve weeks of RT was effective in improving MFS for both CON and ECC contractions, while improvement in MFA was attained only during ECC contractions. MFS improved for different age groups under certain conditions with practice, yet differ between age groups. As MFA was associated with FMT during ECC contractions, it may be linked to impaired mobility in OIA. Improvements in MFS and MFA are attainable with RT.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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CHAPTER 1

INTRODUCTION

Currently, the number of older adults in the United States exceeds 35 million and this number is anticipated to increase two fold by 2030, and grow further to 89 million by 2050 (B. G. S. American Geriatrics Society, 2010; B. G. S. American Geriatrics Society, and American Academy of Orthopadedic Surgeons, 2001). Some noticeable age-related challenges experienced by older adults include impairments in muscle function and mobility which increase the risk for falling (Carville, Perry, Rutherford, Smith, & Newham, 2007; Delbaere, 2003; Rubenstein, 2006; Schiffman, Luchies, Richards, & Zebas, 2002; Shumway-Cook, Brauer, & Woollacott, 2000). Notably, one-third of adults age 65 and older will experience a fall annually (B. G. S. American Geriatrics Society, 2010). It is intuitive to link maximal muscle strength and power capabilities with impaired mobility and falling, however, the ability to perform day-to-day tasks does not typically require maximal capabilities, which are typically tested, but rather submaximal muscle function capabilities (Hortobagyi, Mizelle, Beam, & DeVita, 2003). Accordingly, the inability of older adults to control submaximal muscle forces may also contribute to deteriorating levels of mobility and increased fall risks.

The neuromuscular system declines with aging whereupon reduced motor performance occurs (Aagaard, Suetta, Caserotti, Magnusson, & Kjaer, 2010; Kornatz, Christou, & Enoka, 2005). For example, when a muscle contracts, the force that is produced tends to fluctuate around an average value (Christou & Carlton, 2002; Enoka et al., 2003; Galganski, Fuglevand, & Enoka, 1993; Krishnan, Allen, & Williams, 2011; Tracy, Byrnes, & Enoka, 2004), however, the variability in force fluctuations is often greater in older adults compared to young adults (Doherty, 2003; Galganski et al., 1993). Further, the diminished ability of older adults to regulate force output may negatively impact their ability to perform daily mobility tasks including rising from a chair, ascending or descending stairs or walking (Christou, Shinohara, & Enoka, 2003; Delbaere, 2003; Hortobagyi et al., 2003; Kornatz et al., 2005; Seynnes et al., 2005).

Muscle Force Steadiness and Accuracy

One approach used to detect changes in decreased motor performance over the lifespan is to measure the ability of an individual to maintain a constant or steady force, often referred to as muscle force steadiness (MFS), relative to a target force during a submaximal muscle contraction (Enoka et al., 2003; Marmon, Gould, & Enoka, 2011; Tracy & Enoka, 2002). In general, older adults tend to demonstrate greater variability in MFS when performing submaximal muscle contractions compared to young adults (Christou & Enoka, 2011; Hortobagyi, Tunnel, Moody, Beam, & DeVita, 2001; Laidlaw, Kornatz, Keen, Suzuki, & Enoka, 1999; Vaillancourt, Larsson, & Newell, 2003). However, the reported results have varied depending on the type of muscle contraction and the muscle group tested (Enoka et al., 2003). Older adults demonstrate greater variability in MFS when performing submaximal isometric muscle contractions compared to younger adults with the first dorsal interosseus muscle of the hand, elbow flexors and knee extensors (Burnett, Laidlaw, & Enoka, 2000; Galganski et al., 1993; Hortobagyi et al., 2001; Keen, Yue, & Enoka, 1994; Laidlaw, Bilodeau, & Enoka, 2000;

Sorensen et al., 2011; Tracy & Enoka, 2002). Further, older adults tend to demonstrate greater variability in MFS when performing eccentric (ECC) lengthening contractions compared to concentric (CON) or isometric (ISOM) muscle contractions (Graves, Kornatz, & Enoka, 2000; Hortobagyi et al., 2001). It may be that the impaired ability to control ECC MFS in older adults may confer an increased risk for falling, particularly during eccentric-dependent tasks like descending stairs (Carville et al., 2007; Hortobagyi et al., 2003). In addition to MFS, muscle force accuracy (MFA), has also been utilized to measure the control of submaximal force output (Hortobagyi et al., 2001). Specifically, MFA can be characterized as the ability of an individual to maintain or keep an average force on a target force for a brief period of time, as the average distance away from the target is the measure of MFA (Hortobagyi et al., 2001). Though the data regarding MFA is limited and infrequently reported compared with MFS, MFA has been found to be impaired in older adults during relatively slow contractions and in rapid discrete contractions (Christou, Poston, Enoka, & Enoka, 2007; Christou et al., 2003; Hortobagyi, Garry, Holbert, & Devita, 2004; Hortobagyi et al., 2001). For example, Hortobagyi et al. (2001) reported that older adults demonstrated twice the amount of target force error during CON contractions and three times the amount of the target force error during ECC contractions (Hortobagyi et al., 2001). While older adults tend to demonstrate greater variability in controlling submaximal muscle contractions, they may be able to acquire or learn how to obtain stable MFS measures with practice (Floyer-Lea & Matthews, 2005). Unfortunately, there is a limited amount of evidence regarding the amount of practice needed, or how rapidly an individual can acquire, the ability to maintain steady and accurate forces across repeated trials. This may have an impact on whether MFS measures differ across the lifespan.

Fall Risk and Potential Muscle Contributors

Major challenges can exist for the greater than one-third of older adults that experience a fall (B. G. S. American Geriatrics Society, and American Academy of Orthopadedic Surgeons, 2001; Tinetti, Speechley, & Ginter, 1988). Unintentional injuries resulting from a fall are currently the fifth leading cause of death (Rubenstein, 2006; Tinetti & Kumar, 2010). Unfortunately, some older adults who have experienced a fall can become overly cautious and consequently tend to decrease their risk by limiting their daily activities (Callisaya et al., 2011; Rubenstein, 2006; Tinetti et al., 1988). Accordingly, diminished activity levels in older adults may also contribute to deconditioning, muscle weakness, and ultimately decreased mobility (Tinetti & Kumar, 2010). The decline in muscle strength coupled with diminished activity levels in older adults who have fallen may also contribute to increased fall risks in this needy population, particularly when performing mobility tasks such as walking, rising from a chair or when ascending or descending stairs (Callisaya et al., 2011; Hortobagyi et al., 2003; Oh-Park, Wang, & Verghese, 2011; Rubenstein, 2006; Shumway-Cook et al., 2000; Startzell, Owens, Mulfinger, & Cavanagh, 2000). Although older adults may be able to generate force levels that are adequate to perform these tasks, the optimal performance of such tasks may be impaired due to decreased control of submaximal force output when a muscle contracts (Galganski et al., 1993; Hortobagyi et al., 2003; Seynnes et al., 2005). Since older adults tend to demonstrate greater variability, particularly when performing eccentric contractions, in controlling submaximal forces that are both steady and accurate, this may have a negative impact on the ability of older adults who have fallen to perform mobility tasks and potentially increase their risk for falling (Carville et al., 2007; Oh-Park et al., 2011; Schultz, 1992). Interestingly, no evidence has been reported whether associations exist between submaximal force control of older adults who have experienced a fall and their ability to perform functional mobility tasks.

Resistance Training and Multicomponent Fall Reduction Exercise

The orchestration and implementation of countermeasures to improve muscle strength, and reduce the variability in submaximal force control in older adults, particularly in those who have experienced a fall, is desirable. One countermeasure reported to be effective in improving strength and submaximal force control is resistance exercise training (Hortobagyi et al., 2001; Kornatz et al., 2005; Laidlaw et al., 1999; Tracy et al., 2004). For example, when resistive exercise training is performed with the first dorsal interosseus muscle of the hand significant improvements occur in both muscle strength and submaximal force control (Keen et al., 1994; Kornatz et al., 2005; Laidlaw et al., 1999). When resistance exercise training is performed with the knee extensor muscles, significant improvements in muscle strength and submaximal force control can also be obtained (Hortobagyi et al., 2001; Tracy et al., 2004).

Countermeasures designed to reduce fall risks in older adults, including those who may have experienced a fall, tend to be multifactorial and incorporate varying exercises aimed at increasing muscle strength, improving balance, educating the patient regarding potential risk factors, and a home safety assessment (B. G. S. American Geriatrics Society, 2010; Gillespie et al., 2012; Steinberg, Cartwright, Peel, & Williams, 2000). Multicomponent exercise fall reduction programs have been reported to be effective in improving strength and reducing the risk for falls in older adults (B. G. S. American

Geriatrics Society, 2010; B. G. S. American Geriatrics Society, and American Academy of Orthopadedic Surgeons, 2001; Braun, 1998; Goodwin et al., 2014; Province et al., 1995; Shumway-Cook, Gruber, Baldwin, & Liao, 1997).

Resistance exercise training using negative eccentric work has also been reported to be a safe, yet effective method in improving strength with varying rehabilitation groups (Dibble, Hale, Marcus, Gerber, & Lastayo, 2006; Gerber, Marcus, Dibble, Greis, & LaStayo, 2006; P. LaStayo, Marcus, Dibble, Frajacomo, & Lindstedt, 2013; P. C. LaStayo, Marcus, Dibble, Smith, & Beck, 2011; Marcus, Lastayo, Dibble, Hill, & McClain, 2009). Improving muscle strength in older adults who have fallen with eccentric resistance training is interesting and may be of additional benefit to this group of individuals, particularly when performing tasks that require eccentric contractions such as descending stairs. An additive benefit is that this eccentric countermeasure can be utilized with low levels of exertion in order to produce high levels of muscle workloads, resulting in improved strength and mobility (P. C. LaStayo, Ewy, Pierotti, Johns, & Lindstedt, 2003). As the variability in submaximal force control tends to be greater when performing eccentric muscle contractions in older adults, the coupling of a multicomponent exercise fall reduction program which includes resistance exercise via negative eccentric work may be effective in not only improving strength, balance and mobility in older adults who have fallen, but may also improve their ability to control submaximal force output.

Next Chapters of the Dissertation

The second chapter of this dissertation will examine whether a submaximal muscle force control practice effect, or skill acquisition, occurs when performing CON and ECC MFS measures of the knee extensor muscles in healthy young, healthy old and older adults who have fallen. The third chapter will then compare whether there is a difference in MFS when performing CON and ECC muscle contractions of the knee extensors between the three different cohorts. Chapter 4 will expose whether there is an association between either MFS or MFA of the knee extensors and functional mobility tasks such as the 6 minute walk, the timed up and go test, stair ascent and stair descent. Finally, in Chapter 5 a test of specific resistance exercise modes on MFS and MFA will be explored. Specifically, training utilizing a multicomponent falls reduction program where either a traditional resistance exercise (standard of care) or resistance exercise training utilizing negative eccentric work of the lower extremities will be compared to determine whether improvement in MFS and MFA are attainable following 12 weeks of training.

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CHAPTER 2

VARIABILITY OF MUSCLE FORCE STEADINESS AND PRACTICE

Introduction

It can be challenging to improve the motor skill necessary to minimize the variability in muscle forces. The amplitude of fluctuations in muscle force is characterized as muscle force steadiness (MFS). Impaired MFS (i.e., high levels of variability in the muscle's force output) is one of the motor consequences of aging (Christou & Enoka, 2011; Galganski, Fuglevand, & Enoka, 1993; Laidlaw, Kornatz, Keen, Suzuki, & Enoka, 1999; Marmon, Gould, & Enoka, 2011). This impairment is especially evident when the motor tasks require submaximal efforts (Enoka et al., 2003; Keen, Yue, & Enoka, 1994; Laidlaw, Bilodeau, & Enoka, 2000). Reports of impaired MFS have stemmed largely from experiments involving isometric contractions (Christou & Carlton, 2002; Krishnan, Allen, & Williams, 2011; Seynnes et al., 2005; Taylor, Christou, & Enoka, 2003; Tracy & Enoka, 2002; Vaillancourt & Newell, 2003). However, daily activities are rarely isolated to isometric contractions alone, nor do these activities require maximal efforts. Rather, it is during submaximal shortening-concentric and lengthening-eccentric muscle activities that impaired MFS may adversely impact movement precision and daily activities (Daselaar, Rombouts, Veltman, Raaijmakers, & Jonker, 2003; Delbaere, 2003; Galganski et al., 1993; Hortobagyi & DeVita, 1999;

Larsen, Sorensen, Puggaard, & Aagaard, 2009; Seynnes et al., 2005).

Because the ability to maintain a steady muscle force involves continuous adjustment of the descending command during the integration of various afferent inputs, it is possible that improved steadiness may be acquired during repeated performance of even the simplest steadiness tasks (Floyer-Lea & Matthews, 2005). However, little information exists that describes how quickly a person acquires the skill of maintaining a steady force when repeated MFS trials are performed. Skill acquisition during novel motor tasks can be challenging for older adults (Brown, Robertson, & Press, 2009; Daselaar et al., 2003; Light, 1990; Seidler, 2006; Wishart & Lee, 1997). According to Magill (2011), motor learning or skill acquisition can be subdivided into three phases namely, early acquisition, retention and transferability. Early acquisition refers to the initial changes that occur in performance due to repeat exposures of the task. Retention involves the ability to perform the task following a brief or specified time period where the individual has no exposure or practice of the task (within session or between session). Transferability involves the performance of a similar task, yet different from the task performed during the early acquisition phase (Magill, 2011). Specifically, we are interested in exploring the early acquisition phase of motor learning as it pertains to early performance improvement via practice. Interesting, repeated practice of novel tasks can often (Jordan & Rabbitt, 1977; Light, 1990; Salthouse, 1982), but not always (Buch, Young, & Contreras-Vidal, 2003; Harrington & Haaland, 1992; Pratt, Chasteen, & Abrams, 1994; Seidler, 2006, 2007; Strayer & Kramer, 1994), improve performance to levels comparable to young adults. For example, Christou et al. (2007) demonstrated the motor force output ability of older adults to reach a target endpoint accurately during rapid (150ms), discrete force tasks matched that of young adults after about eight blocks of five trials (Christou, Poston, Enoka, & Enoka, 2007). Additionally, one study reported an ancillary finding from a small sample (*n*=6) that suggested no further improvements in MFS after 10 practice trials (Hortobagyi, Tunnel, Moody, Beam, & DeVita, 2001). The sample did not include a variety of younger and older adults, nor did it include functionally impaired individuals. Therefore, the literature is limited regarding motor skill acquisition specifically related to MFS measures. The purposes of this study were to determine whether MFS variability improves following repeated bout performance of concentric and eccentric contractions of the knee extensors; and to determine whether young, old and old impaired adults vary in the number of practice or familiarization trials needed to obtain stable MFS measures.

Methods

This study assessed three different cohorts, via a sample of convenience, of healthy young adults (HYA), healthy older adults (HOA) and older-impaired adults (OIA), who volunteered to participate in a 2.5 hour experimental session. Participants were recruited from the University of Utah and the Salt Lake City, Utah community. The HYA and HOA groups ambulated independently in a community setting and were able to perform low to medium levels of physical activity, defined as any aerobic or strength training activity ranging from 3 to 7 days per week and lasting 20-30 minutes in duration. HYA participants were between the ages of 18-30 years; HOA and OIA participants were ≥ 65 years of age, though the latter were characterized as impaired as they must have experienced at least one unintentional fall in the past year and had two or more co-morbid medical conditions. The OIA participants were required to be able to ambulate with or without an assistive device. Exclusion criteria for all participants included progressive neurological disorders, active cancer, chronic heart failure or unstable medical conditions. Participants provided signed confirmation of their informed consent. The Institutional Review Board at the University of Utah approved the procedures used in this study.

Knee Extension Maximal Voluntary Isometric Contraction Measurements

Participants first performed a maximal voluntary isometric contraction (MVIC) of the knee extensor muscles at a joint angle of 45° of knee flexion on a KinCom dynamometer (KinCom 500H, Chattecx Corp; Harrison, TN). Participants were positioned with the hips flexed to approximately 80° and the knees flexed to 90° and secured with straps to prevent any extraneous movements. The rotation center of the knee joint was aligned with the dynamometer axle and the distal lower leg was secured with a strap. Prior to testing, participants performed three submaximal contractions, one at 50% and two at 75% of their perceived maximal effort. Following a rest period of 1 to 3 minutes, participants performed three maximal isometric contractions by pushing as forcefully as they possibly could for 3 seconds, with strong verbal encouragement. The maximal peak torque of the three trials, with a coefficient of variation (CV) no greater than 5% between the three trials, was used as the MVIC. One minute of rest was given between each trial.

Muscle Force Steadiness Measurement

To test MFS, a monitor was placed approximately 1 meter in front of the participant and they were instructed to exert a submaximal knee extension effort to match the target line appearing on the monitor that represented 50% of their MVIC. As the participants applied force to the lever arm, a bold left-to-right scrolling line was produced on the monitor. Participants were instructed to perform the smoothest, most steady contraction as they possibly could by attempting to match his or her force output to the target force line projected on the monitor. Each trial lasted 8 seconds in duration consisting first of a 4 second CON contraction followed by a 4 second ECC contraction of the knee extensor muscles. At any time during the contractions the participant could stop pushing and the machine would stop instantaneously. The dynamometer speed was set at 15 degrees*sec-1 and data were collected for analysis over a 60° range of motion with the starting position being 75° of knee flexion and terminating at 15° of knee flexion. Each participant performed two familiarization trials followed by a series of test trial sequences (TTS) consisting of three trials per sequence with a 1 minute rest period between each trial. Following the completion of each TTS (three trials), participants were given a 3 to 5 minute rest period. Participants performed a total of 10 TTS with the mean of three trials used as the MFS dependent variable. MFS measures were collected on the weaker leg determined by the MVIC force. MFS was characterized by the coefficient of variation (CV=SD/mean force*100), an accepted method for quantifying force variability (Christou & Carlton, 2002; Galganski et al., 1993; Tracy & Enoka, 2002).

Data Processing and the Determination of Motor Skill Acquisition

The analog torque signal from the dynamometer was converted via a digital processor (DAQ-National Instruments, Austin, TX), with a low-pass Butterworth filter at 100 Hz. The middle 2 seconds from each 4 second force trace was used to measure MFS to avoid the ramping up and down phase of force production as the target force was approached. The mean force was calculated from the middle 2 seconds. After linear detrending of the 2 second segment, the mean, standard deviation, and CV (Figure 2.1) were calculated with customized software (Matlab software, Mathworks, Inc.; Natlick, MA, 2009). Submaximal motor skill acquisition was operationally defined as the point at which no further improvement in MFS was detected between TTS blocks.

Statistical Analysis

The dual purposes of this study were to investigate whether repeated testing of MFS resulted in submaximal motor skill acquisition during CON and ECC contractions of the knee extensor muscles, and how many trials were needed to reach a plateau in skill acquisition of MFS during short-term learning by young adults, older adults, and functionally impaired older adults. To assess the groups during both CON and ECC contractions a one-way analysis of variance with repeated measures (RMANOVA) was utilized with TTS as the within-subjects factor.

The dependent variable for each of the TTS was the mean of three trials for that sequence. If a difference ($p \leq 0.05$) across TTS was detected, post hoc pairwise comparisons of each TTS were made using Tukey’s HSD (honestly significant difference). The post hoc pairwise comparisons where no significance differences ($p>$

0.05) were detected would indicate the point at which no additional learning or skill acquisition occurred across TTS.

Results

Participant demographic characteristics are presented in Table 2.1. Significant ($p \leq 0.05$) differences were found for: 1) age between the three groups; 2) weight and height between the OIA and the other two groups; and 3) proportion of men and women between the OIA and HOA. No significant differences were found for BMI. The average of three test trials for each sequence, expressed as the mean CV of force, is depicted in Figure 2.2. A significant ($p < 0.01$) improvement in MFS occurred across TTS for all three groups for both CON and ECC contractions. The mean target force for the MFS trials in the HYA group was 230N ± 70.5N. The HYA group demonstrated an improvement in their MFS from the first to the second TTS, but no further statistically significant improvement thereafter (CON $p = 0.89$, ECC $p = 1.0$). Therefore, motor skill acquisition in the HYA group occurred for CON and ECC contractions after two TTS or a total of six test trials (Table 2.2). The mean target force for the MFS trials in the HOA group was 190N ± 43.8N. The HOA group demonstrated improvements in their MFS for CON from the first to third TTS, but no further statistically significant improvement thereafter (CON $p = 1.0$). In addition, the HOA demonstrated improvements in their MFS for ECC from the first to second TTS, but no further statistically significant improvement in MFS thereafter (ECC $p = 1.0$). Therefore, motor skill acquisition in the HOA group occurred after three TTS for CON or nine test trials and two TTS or six test trials for ECC (Table 2.2). The mean target force for the OIA group was 136N ± 34.1N. The OIA group demonstrated an improvement in their MFS from the first to the second

TTS, but no further statistically significant improvement occurred thereafter (CON p =1.0, ECC p = 0.31). Therefore motor skill acquisition in the OIA group occurred for CON and ECC contractions after two TTS or a total of six test trials (Table 2.2).

Discussion

The purpose of this study was to determine: 1) if repeated testing of MFS reduces the variability of submaximal motor output during CON and ECC contractions of the knee extensor muscles, and 2) how many trials are needed to reach a plateau in skill acquisition of MFS during short-term learning. The results indicated that young adults, older adults, and older-impaired adults did improve and experienced a reduction in submaximal motor output variability of the knee extensor muscles with repeated trials.

Reported evidence on MFS and skill acquisition during repeated tasks with the knee extensors is very limited. For example, as part of a methodological control in their training and steadiness study, Hortobagyi et al. (2001) reported ancillary results from a pilot study (n=6) indicating that following 10 practice trials of CON and ECC contractions on an isokinetic dynamometer, no further significant improvements in MFS skill acquisition were detected within the same session or in a follow up test session repeated 4 weeks later (Hortobagyi et al., 2001). However, they elected to use an absolute submaximal target force of 25N and not a relative submaximal target force based on a percentage of the participants' MVIC as reported by others (Galganski et al., 1993; Hart & Tracy, 2008; Kornatz, Christou, & Enoka, 2005; Sosnoff & Newell, 2006b; Sosnoff & Voudrie, 2009; Tracy, Byrnes, & Enoka, 2004; Tracy & Enoka, 2002; Vaillancourt & Newell, 2003). Interestingly, our findings were similar and novel in that several repeated trials were sufficient not only for the healthy groups (HYA and HOA) but also for the functionally impaired group (OIA) to demonstrate short-term learning effects. Likewise, Sorensen et al. (2011) allude to 10 practice trials (50N and 20N target forces) as adequate (Sorensen et al., 2011). However, they did not report how they determined this specific number of practice trials, therefore precise interpretation of the learning effects is difficult. Hence to date, no study has specifically addressed whether repeated trials testing of MFS measures improves skill acquisition in young and older adult groups, healthy or impaired.

Many have reported that the acquisition of new motor skills can be challenging for older adults and especially so for older-impaired adults (Light, 1990; Seidler, 2006; Wishart & Lee, 1997). However, skill acquisition can occur in older adults during repeated testing of motor tasks of hand muscles, particularly when the task is performed in a block designed order (Daselaar et al., 2003; Durkin, Prescott, Furchtgott, Cantor, & Powell, 1995). While the magnitude and rate of improved skill acquisition is greater for young adults, older adults can experience significant improvements in skill acquisition. We have shown here that even OIA can improve with repeated exposure to CON and ECC MFS tasks. However, the OIA and HOA groups continued to demonstrate greater variability in MFS than the HYA group. Such findings suggest that regardless of the effects of practice, age and frailty may create MFS deficits that may have functional implications.

Repetition and practice can improve performance (Karni et al., 1998; Lee, Swanson, & Hall, 1991). For example, Whitacre and Shea (2000) reported that force error was reduced following a relatively small amount of practice trials when performing a force modulation task (Whitacre & Shea, 2000). Further, some have reported that novel motor tasks practiced in a systematic or fixed repetitive order, often referred to as a block design practice schedule, consistently result in early improved performance (Brown et al., 2009; Daselaar et al., 2003; Jamieson & Rogers, 2000; Schmidt, 1991; Shea & Morgan, 1979). Our findings concur with these findings in that our participants performed test trials in a blocked design schedule and acquired the motor skill with repeated trials. Notably, however, blocked design practice can improve performance during the initial skill acquisition of a motor task, though it may not produce much improvement in long-term retention or transferability (Floyer-Lea & Matthews, 2005; Schmidt, 1991; Schmidt & Bjork, 1992; Shea & Morgan, 1979). Long-term retention of motor skills may require additional practice sessions (Floyer-Lea & Matthews, 2005) though the mechanisms involved in the early skill acquisition performance may trigger central nervous system processes that comprise learning and the formation of motor memory. Further, the initial phase of motor memory formation, namely encoding, requires the acquisition of a motor skill via practice. More specifically, cognitive processes identify the stimulus (new motor task), response selections are then made (supraspinal processing resulting in a descending command) and then a motor response is executed during the encoding phase. Then, following the execution of the motor task, the learner evaluates the outcomes through feedback mechanisms and this information is then used to regulate subsequent movements (Kantak & Winstein, 2012).

Other possible mechanisms underlying improvements in performance may be attributed to feedback control within the CNS which can dampen the variability in the motor output resulting in improved motor skill acquisition (Christou, 2011; Christou et al., 2007; Scott, 2004; Tracy, 2007). Christou et al. (2007) reported that following a blocked design practice schedule of 40 trials of goal-directed isometric contractions of the first dorsal interosseus muscle, older adults were able to improve their MFS to levels commensurate with young adults (Christou et al., 2007). This improvement in steadiness was attributed to the ability of older adults to change the amplitude and timing of the antagonistic muscle (Christou & Enoka, 2011; Enoka et al., 2003). Knight and Kamen also reported that improvements in early skill acquisition were achieved throughout the repeated (*n*=15) performance of isometric contractions of the first dorsal interosseus muscle relative to a force-matching task in young adults (Knight & Kamen, 2004). These reported improvements in early skill acquisition were attributed to more precise modulation of motor unit discharge rate variability.

The processing of visuomotor feedback also likely plays a role during motor skill acquisition (Christou & Enoka, 2011; Sosnoff & Newell, 2006a) as older adults' impaired MFS levels are thought to be linked to an impaired processing of visual feedback. For older adults, the descending motor command to motor neurons when visuomotor information is processed results in greater motor output variability (Tracy, 2007; Tracy, Dinenno, Jorgensen, & Welsh, 2007). In addition to visual feedback, sensory feedback from muscle spindle, tendon organ, and joint and cutaneous receptors (Enoka et al., 2003; Schmidt & Lee, 2011) may also contribute to corrections in the overall descending command that regulates the activation of the motor neuron pool and the discharge rate of motor units (Taylor et al., 2003). Then, based on the intensity level of the contraction, the resulting force output will fluctuate during the execution of movement (Enoka et al., 2003; Schmidt & Lee, 2011; Tracy et al., 2007). Collectively, the execution of a novel task and short-term improvements in motor skill acquisition appear to be linked to the amount and quality of sensory and proprioceptive feedback to the central nervous system thereby influencing the descending command and respective motor output (Christou, 2011; Tracy, 2007). One additional process, which may also contribute to early improvements in performance, is that practice may cause learning dependent changes in the functional network of the brain and these networks may represent motor memory (Floyer-Lea & Matthews, 2004; Kantak & Winstein, 2012).

One possible limitation of this study is that there may have been a systematic order effect which could have occurred when MFS was measured as each participant performed CON MFS measures first, then ECC MFS measures second. However, this methodological sequencing may also be compared to block design learning in that participants perform the same task in the same order over repeated trials, which has been reported to produce early improvements in skill acquisition (Lee et al., 1991).

It is unknown how many practice trials are needed to produce stable MFS measures in different age groups. Established standards for the number of practice trials necessary will allow researchers to more precisely explore the efficacy of treatment interventions such as resistance training, steadiness training, or balance training in reducing motor output variability or improving activities of daily living such as descending stairs or inclined surfaces.

Conclusion

A limited number of practice trials can elicit reductions in force variability (i.e., MFS) during repeated submaximal concentric and eccentric contractions of the knee extensor muscles. Healthy young adults, older adults, and older-impaired adults accomplish the majority of this learning within six to nine trials. These novel findings may provide a framework for improving methodological approaches in obtaining stable MFS measures prior to testing MFS in trials with various populations.

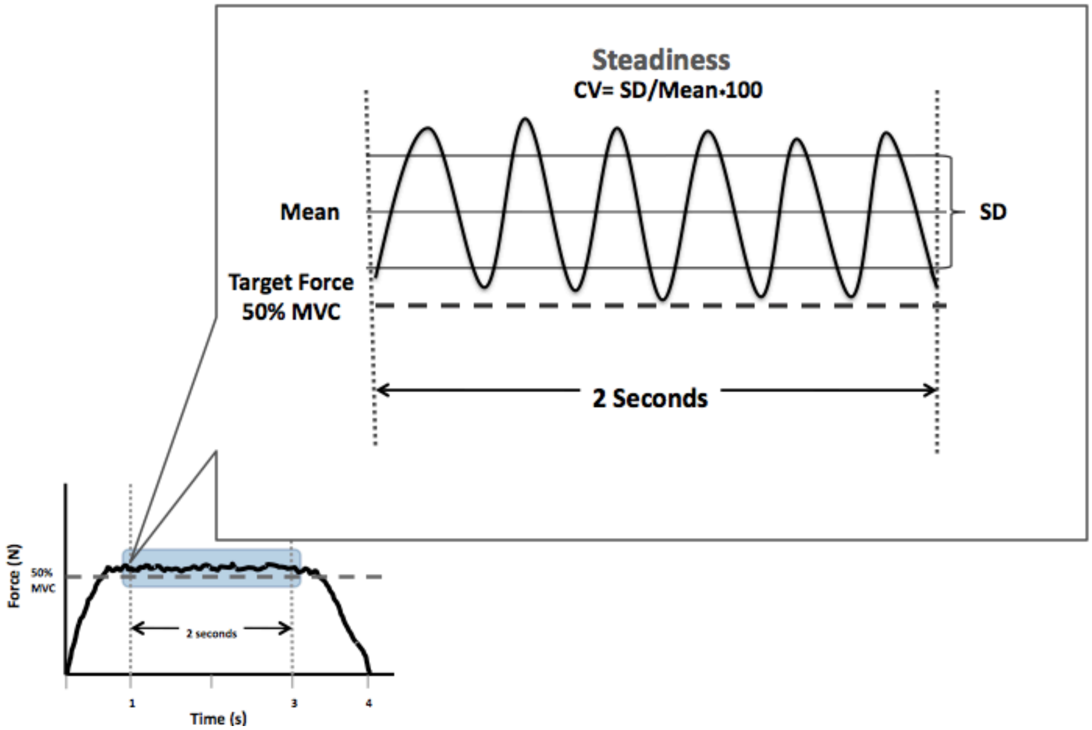
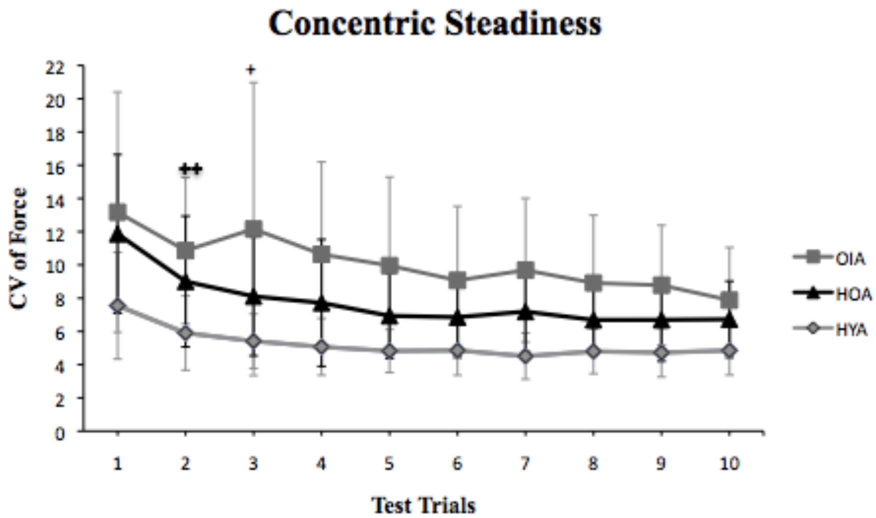


Figure 2.1 – Example of the MFS measurement. The illustration on the lower left represents a force trace of an MFS trial over a 4 second time interval recorded during CON or ECC contractions. The enlarged illustration represents the middle 2 second interval used to calculate MFS expressed as the CV of force.

A)



B)

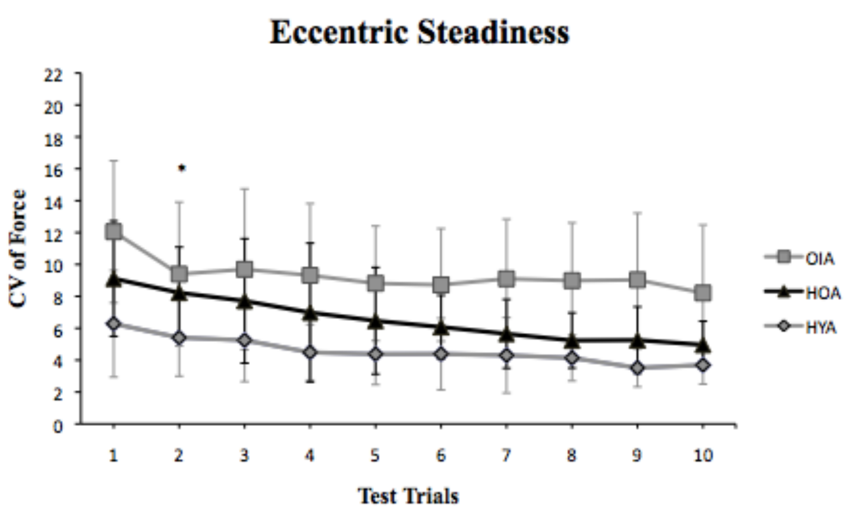


Figure 2.2 – Skill acquisition, seen as improvement of MFS measures, expressed as the mean CV of force, over 10 test trial sequences (TTS) for the three groups (error bars represent standard deviation). A) Depicts CON MFS trials. B) Depicts ECC MFS trials.

+ = No significant difference detected with RMANOVA for remaining trials for HOA with CON MFS (p>0.05)

++ = No significant difference detected with RMANOVA for remaining trials with HYA and OIA Fallers with CON MFS (p>0.05)

* = No significant difference detected with RMANOVA for remaining trials for all groups with ECC MFS (p>0.05)

Table 2.1 - Participant characteristics

Participant Demographics	Healthy Young Adults	Healthy Old Adults	Old Impaired Adults
Males/Females	10/10	15/5	5/15
Mean Age (yrs)	24.4 [22.72, 25.98]	70.6 [68.87, 72.33]	77.5 [74.16, 80.74]
Height (cm)	176.0 [170.43, 181.60]	176.2 [172.11, 180.33]	166.4 [162.27, 170.53]
Weight (kg)	77.0 [67.28, 86.79]	85.8 [79.61, 92.06]	69.5 [61.92, 77.02]
BMI (Kg/m2)	24.6 [22.40, 26.76]	27.6 [26.13, 28.97]	25.14 [22.31, 27.97]

Each group contained 20 participants, (*n*=60). Values for gender, age, height, weight and BMI are group means and 95% C.I.

Table 2.2 Group mean MFS measures expressed as the CV of force and number of test trial sequences completed during skill acquisition and attainment of stable MFS measures

Group & TTS		MFS CON ± SD	Skill Acquisition	MFS ECC ± SD	Skill Acquisition
HYA	1	7.55 ± 3.21		6.28 ± 3.34	
	2	5.91 ± 2.24	$p = 0.89$	5.41 ± 2.42	$p = 1.0$
	3	5.42 ± 1.64		5.25 ± 2.60	
HOA	1	11.86 ± 4.78		9.11 ± 3.62	
	2	9.00 ± 3.93		8.23 ± 2.86	$p = 1.0$
	3	8.11 ± 3.58	$p = 1.0$	7.71 ± 3.90	
OIA	1	13.17 ± 7.23		12.05 ± 4.45	
	2	10.86 ± 4.40	$p = 1.0$	9.39 ± 4.51	$p = 0.31$
	3	12.16 ± 8.81		9.70 ± 5.04	

Values are group means ± SD for each contraction type. *P* values depict the test sequence where no significant difference was detected (each test sequence contains three test trials).

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CHAPTER 3

MUSCLE FORCE STEADINESS IN THE KNEE EXTENSORS VARIES BETWEEN YOUNG, OLD AND OLD ADULTS WHO HAVE FALLEN

Introduction

When a muscle is activated by the nervous system, the force fluctuates (Enoka et al., 2003; Galganski, Fuglevand, & Enoka, 1993; Tracy, Byrnes, & Enoka, 2004). Measures of muscle force steadiness (MFS) have been used to quantify the fluctuations in force output (Krishnan, Allen, & Williams, 2011; Tracy & Enoka, 2002). Greater fluctuations may adversely impact the ability of an individual to achieve specific limb trajectories and reach desired endpoints (Christou, Poston, Enoka, & Enoka, 2007; Enoka et al., 2003). These impairments in MFS in older individuals have been documented in large part from experiments involving isometric contractions. However, some assessment of anisometric MFS has also been performed, and these outcomes may be more relevant to functional task performance (Seynnes et al., 2005). In older adults the MFS of index finger abductors, elbow flexors, and knee extensors is impaired at lower target forces during isometric contractions when compared with young adults (Burnett, Laidlaw, & Enoka, 2000; Galganski et al., 1993; Hortobagyi, Tunnel, Moody, Beam, & DeVita, 2001; Keen, Yue, & Enoka, 1994; Laidlaw, Bilodeau, & Enoka, 2000; Tracy & Enoka, 2002). Further, older adults have exhibited greater force output variability during anisometric contractions of the elbow flexors and knee extensors compared with young adults (Graves, Kornatz, & Enoka, 2000; Hortobagyi et al., 2001). However, evidence of no differences has also been reported (Burnett et al., 2000; Enoka et al., 2003; Laidlaw, Kornatz, Keen, Suzuki, & Enoka, 1999; Tracy & Enoka, 2002). Additionally, when target forces were ≥50% of MVIC or when larger muscle groups were tested, others have reported no differences in MFS between young and old adults (Christou & Carlton, 2001; Enoka et al., 2003; Tracy & Enoka, 2002).

The performance of many daily activities utilizes anisometric shortening and lengthening muscle contractions, but little is known about MFS in functionally affected populations, such as older adults who have experienced a fall. Since impaired submaximal force control may adversely impact movement precision (Delbaere, 2003; Larsen, Sorensen, Puggaard, & Aagaard, 2009; Seynnes et al., 2005), identifying clinical populations with unsteady force control is important. For example, Hortobagyi et al. (2004) reported that in populations with knee osteoarthritis, the variability in MFS was greater during concentric and especially eccentric contractions of the knee extensor muscles in aged and gender match comparisons. Further, Carville et al. (2007) investigated MFS in healthy older adults and older fallers at low force levels and reported that the force variability was greater for fallers than nonfallers during anisometric contractions, especially during eccentric contractions. However, it is unknown whether older adults who have fallen may experience difficulty in controlling submaximal force output at a moderate force level (50% MVIC). To our knowledge, there has been only limited reported evidence on observations as to whether MFS differs between healthy and older adults who have fallen.

Thus, the purpose of this study was to compare MFS during submaximal CON and ECC contractions of the knee extensor muscles between healthy young (HYA) and healthy old adults (HOA), and old impaired adults who have fallen (OIA-fallers). Due to the greater neuromuscular decline in elderly adults with functional impairment, we hypothesized that there will be no differences detected in MFS during submaximal contractions of the knee extensor muscles between the HYA and HOA, but that a difference in MFS will be detected between the HOA compared to the OIA-fallers.

Methods

This cross-sectional study consisted of 60 individuals making up three distinct groups: HYA (*n*=20, 10 males, 10 females; 24.4 $\pm$ 3.5yrs; range 18-30yrs), HOA (*n*=20, 15 males; 5 females; 70.6 $\pm$ 3.7 yrs, range 66-80yrs) and OIA-fallers (*n*=20, 5 males; 15 females; 77.5 $\pm$ 7yrs, range 67-90yrs) who volunteered to participate in a single 2.5 hour experimental session. Participants were recruited from the University of Utah and the Salt Lake City community and written informed consent was obtained. The Institutional Review Board at the University of Utah approved the procedures.

The HYA and HOA groups ambulated independently and participated in low to medium levels of physical activity, defined as any aerobic or strength training activity ranging from 3-7 days per week, lasting 20-30 minutes in duration. The OIA group consisted of older adults who had experienced at least one unintentional fall in the past year, had at least two co-morbid conditions and were enrolled and preparing to participate in a multicomponent falls reduction study. Exclusion criteria included progressive neurological disorders, active cancer, chronic heart failure or unstable medical conditions.

Maximal Voluntary Isometric Contraction

In order to determine a 50% submaximal target force for MFS testing, participants initially performed a maximal voluntary isometric contraction (MVIC) of the knee extensor muscles at a joint angle of 45° of knee flexion on a KinCom dynamometer (KinCom 500H, Chattecx Corp; Harrison, TN). Participants were seated with the hips flexed to approximately 80° and the knees at 90°. The center of rotation of the knee joint was aligned with the dynamometer axle. The proximal thigh and hip were secured to the chair with straps and the shank was secured to the shaft of the dynamometer with a strap just proximal to the medial malleolus. For familiarization, participants performed three submaximal trials at approximately 50% effort. After a rest period of 1 to 3 minutes, participants performed maximal isometric trials. Force was ramped up to maximal over approximately 3 seconds and participants were given strong verbal encouragement during the 2 to 3 second maximal effort. Three trials were performed with a 1 minute rest between trials. Each leg was tested. The peak torque of the three trials was used as the MVIC value (peak force coefficient of variation < 5% across trials). If a CV <5% was not obtained a fourth trial was performed.

Muscle Force Steadiness

Testing of MFS consisted of participants matching a target force line representing 50% MVIC while performing concentric (CON) and eccentric (ECC) knee extensor contractions. As participants applied force on the lever arm, a scrolling line was produced on the monitor. The monitor was positioned approximately 1 meter in front of the participants. Participants were instructed to perform the smoothest, most steady contraction possible while attempting to match the target force line. At anytime during

MFS testing participants could stop pushing against the lever arm and the machine would stop instantaneously.

The dynamometer speed was set at 15 deg*sec-1 and data were collected over a total range of motion of 60° (75-15° of knee flexion) during CON and ECC contractions. Each subject performed two familiarization trials followed by a series of 10 test trial sequences (TTS) consisting of 3 trials per sequence or a total of 30 trials. Each trial lasted 8 seconds (4 seconds for CON and 4 seconds for ECC contractions). Participants were given a 1 minute rest period between each test trial and a 3 to 5 minute rest period between each TTS. MFS measures were collected on the weaker of the two lower extremities determined by the MVIC. MFS was characterized by the coefficient of variation (CV=SD/mean force*100), an accepted method for quantifying normalized force variability (Christou & Carlton, 2002a; Galganski et al., 1993; Tracy & Enoka, 2002). In pilot work, it was determined that following nine practice trials of submaximal CON and ECC contractions of the knee extensor muscles, no further statistically significant improvements in MFS were detected with repeated trials within the same session (unpublished data). Therefore, the initial three TTS (nine trials) were considered practice or familiarization trials and were not included as part of the data analysis. The remaining seven TTS were used to measure MFS. MFS testing trials that were ± 20% of the target force were included in the data analysis (Figure 3.1).

Data Processing

The analog torque signal from the KinCom dynamometer was converted via a digital processor (DAQ-National Instruments), with a low-pass butterworth filter at 100 Hz. The middle 2 seconds from each 4 second force trace during CON and ECC contractions was used to measure MFS, avoiding the ramping up and down of force during target force acquisition. The mean force was calculated from the middle 2 second period. After linear detrending, the standard deviation and CV of MFS were calculated using custom Matlab software (Mathworks, Inc.; Natlick, MA, Matlab 2009).

Statistical Analysis

The primary purpose of this study was to compare MFS (CV of force) during submaximal CON and ECC contractions of the knee extensor muscles between groups (HYA, HOA and OIA-fallers). The CV of force was compared between groups (between subjects factor = group) using separate one way ANOVAs for CON and ECC contractions (SPSS version 21). Post hoc comparisons with Tukey's HSD were used to detect specific between-group differences when the overall ANOVA comparison was significant.

Results

Subject characteristics are summarized in Table 3.1. Significant differences ($p<0.05$) were detected for age, height, weight and maximal knee extension strength, respectively. The OIA-fallers group were significantly older, shorter in height, and weaker in MVIC strength compared to the HOA and HYA groups, and lighter in weight only with the HOA group. The HOA group was significantly older and weaker than the HYA group. The average number of co-morbidities within the OIA-fallers participants was 4.2 ± 2.6. Accompanying conditions included hypertension, osteoarthritis (hand, wrist), cerebral vascular accident, depression, scoliosis, lung disease, ulcer (esophageal), high cholesterol, sleep apnea, joint replacement (hip, knee, shoulder), acid reflux, diabetes, hypothyroid, and completion of treatment regime for cancer (breast, colon, prostate).

Muscle Strength

The MVIC force was significantly different between the groups ($P<0.05$) with the OIA-fallers being 52% weaker than the HYA group and 34% than the HOA group (see Table 3.1). MVIC force for the HOA was reduced by 19% compared with the HYA group ($P<0.05$).

Muscle Force Steadiness

When comparing CON contractions of the knee extensors, a significant difference in MFS was detected between the groups ($P<0.05$) as the OIA-fallers group demonstrated greater unsteadiness than the HOA and HYA, with the HYA being the most steady (see Table 3.2). During ECC contractions of the knee extensors, significant differences in MFS were also detected between the groups ($P<0.05$) as the OIA-fallers demonstrated greater unsteadiness than the HOA and HYA groups. However, no significant differences ($P=0.55$) were detected between the HYA and HOA groups (see Figure 3.2).

Discussion

The purpose of this study was to determine the differences in concentric and eccentric force control of the knee extensors between older fallers, healthy older adults and young adults. The main findings were: 1) for concentric contractions, the age-related impairment in force steadiness observed in healthy older adults is even greater for older fallers, and 2) during eccentric contractions, older fallers are significantly less steady than healthy older adults and young adults; with no significant differences observed between healthy older adults and young adults.

The weight of the available evidence supports the notion of greater force variability for older compared with young adults, particularly at low target force levels, during either isometric or anisometric muscle contractions, and with a single agonist muscle or group of muscles (Burnett et al., 2000; Galganski et al., 1993; Hortobagyi et al., 2001; Laidlaw et al., 1999; Tracy & Enoka, 2002). Our findings of significantly impaired MFS for older adults compared with healthy young adults during CON contractions are in agreement with some (Carville, Perry, Rutherford, Smith, & Newham, 2007; Christou & Carlton, 2002b; Hortobagyi et al., 2001), yet contrast with others (Christou & Carlton, 2001; Tracy & Enoka, 2002).

Data that describe differences in MFS of the knee extensor muscles between healthy older adults and older adults who have fallen are very limited. Only Carville et al. (2007) reported significant differences in ECC, but not CON, MFS measures in older adults who had fallen when compared to older nonfallers or healthy young adults. Our findings were similar, but not identical. We detected a significant difference in MFS between healthy older adults and older fallers for both CON and ECC contractions. However, when comparing the present study with Carville et al. (2007), the methodological approach between the studies differed. For example, Carville et al. (2007) elected to use an absolute target force to measure MFS. To ensure that the net activation of the motor unit pool was similar across participants irrespective of individual differences in strength, we used a similar percentage of the individuals MVIC force to measure steadiness (50% MVIC). Further, the present study employed the use of CON and ECC contractions of the knee extensors as these are dynamic, functional muscle contractions used in the performance of daily activities such walking, stair ascent and descent, or rising or lowering from a chair (Delbaere, 2003; Seynnes et al., 2005). Collectively, the reported results of the present study provide additional information about dynamic force control in older adults, particularly for those who have fallen.

The observation of a decreased ability to control submaximal force output during muscle lengthening may have functional implications in older adults (Grabiner & Enoka, 1995; Hortobagyi et al., 2001; Laidlaw et al., 1999). For example, increased eccentric variability could affect the ability of older adults, particularly those with increased risk of falling or who have fallen, to execute lengthening contractions used in performing daily activities such as descending stairs or ramped surfaces, or lowering oneself into a seated position (Delbaere, 2003; Galganski et al., 1993; Hortobagyi & DeVita, 1999; Larsen et al., 2009; Seynnes et al., 2005). The optimal regulation of force output of the knee extensors is essential to the performance and execution of many daily activities (Hortobagyi, Garry, Holbert, & Devita, 2004).

Resistance training has been reported by others to be an effective intervention in improving MFS (Hausdorff et al., 2001; Hortobagyi et al., 2001; Keen et al., 1994; Laidlaw et al., 1999; Tracy et al., 2004; Tracy & Enoka, 2006). Further, Brown et al. (2009) reported that although general declines in motor execution have been found with aging, older adults were able to improve their motor execution with practice of a motor sequence (Brown, Robertson, & Press, 2009; Kornatz, Christou, & Enoka, 2005). Accordingly, in order to minimize the potential for a practice effect occurring, participants performed nine practice trials prior to collecting MFS measures. Similar findings regarding a specified number of practice trials were also reported by others, although the extent of very short-term learning with repeated steadiness trials has not been clearly elucidated (Hortobagyi et al., 2001; Sorensen et al., 2011).

The neural mechanisms that could potentially explain or account for the differences detected in MFS with the OIA-fallers group include changes in the discharge behavior of motor units, visuomotor processing and unique activation strategies used during eccentric contractions. With aging, the neuromuscular system can undergo changes resulting in loss to motor neurons and muscle fibers, thereby reducing the number and size of motor units (Vandervoort, 2002). However, muscle fibers can experience collateral sprouting from nearby motor neurons thus increasing the size (innervation ratio) of existing motor units (Roos, Rice, & Vandervoort, 1997). It may be that as reorganization of prevailing motor units occur, the exerted force output during a muscle contraction could be elevated thereby creating increased variability in older adults particularly when regulating submaximal muscle forces (Galganski et al., 1993).

The processing of visuomotor feedback may also play a role in force variability between young and old adults (Christou & Enoka, 2011; Sosnoff & Newell, 2006). For example, when an individual attempts to match a force output relative to a target force with visual feedback, the visuomotor input is processed centrally and the descending command to the motor neurons is adjusted to correct the force output (Tracy, Dinenno, Jorgensen, & Welsh, 2007). Accordingly, older adults may experience challenges in processing visual input due to slowing of central processing of visual input (Welsh, Dinenno, & Tracy, 2007). Further, the variability in the descending motor command to the motor neurons when impaired visuomotor information is processed will result in greater variability of the force output (Christou & Enoka, 2011; Fox et al., 2013;

Kennedy & Christou, 2011; Tracy et al., 2007).

The descending command to the motor neurons will also vary when performing CON and ECC contractions when attempting to match a target force. Consequently, the activation of the motor units will not be the inverse function of one another for ECC compared to CON contractions, but may utilize a unique strategy between contraction types as the discharge rate is less during ECC contraction (Duchateau & Baudry, 2013; Duchateau & Enoka, 2008; Enoka, 1996).

One of the limitations of this study was that a single target force was utilized to measure MFS for comparing steadiness between the groups. Having multiple target forces to compare steadiness measures may have produced different results, particularly at lower target forces. That said, the chosen target force was of a functionally relevant intensity such as that observed during stair negotiation, for example.

Conclusion

The steadiness of knee extensor force output varies between healthy young, healthy old and older adults who have experienced a fall. Healthy older adults experienced significantly greater variability with CON, but not ECC MFS when compared to healthy young adults. Older adults who had fallen demonstrated significantly greater variability during both concentric and eccentric knee extensor contractions compared with healthy old and healthy young adults. Further investigations are needed to determine whether increased variability during leg muscle shortening and lengthening, particularly in older impaired adults who have fallen and are functionally impaired, underlies the performance of functional mobility tasks and activities of daily living.

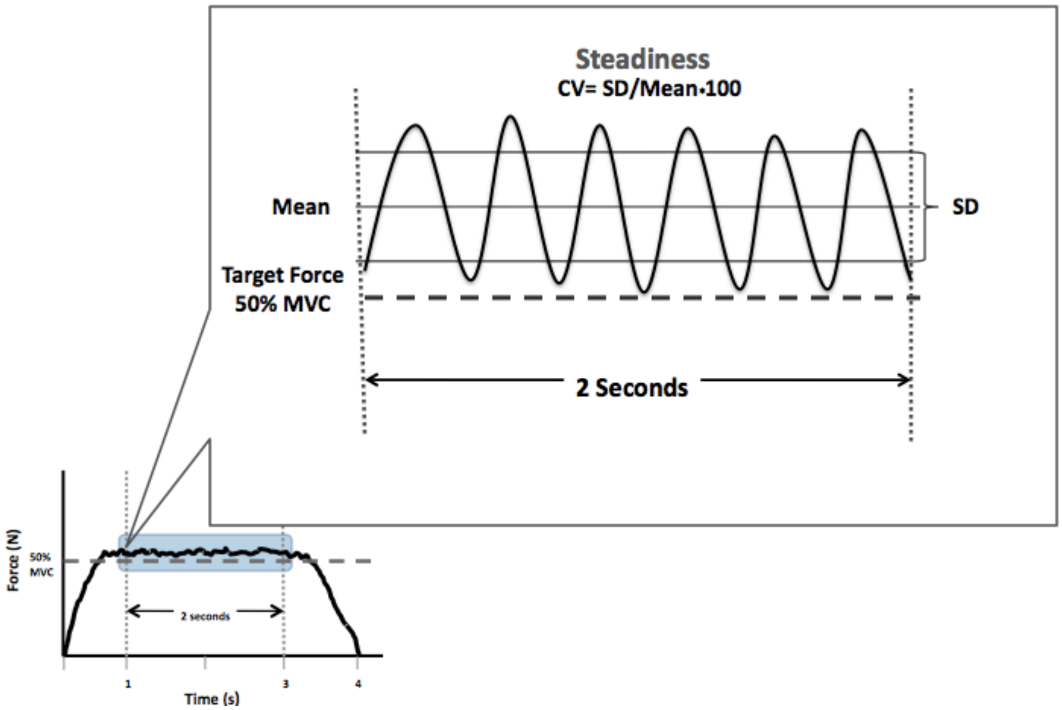
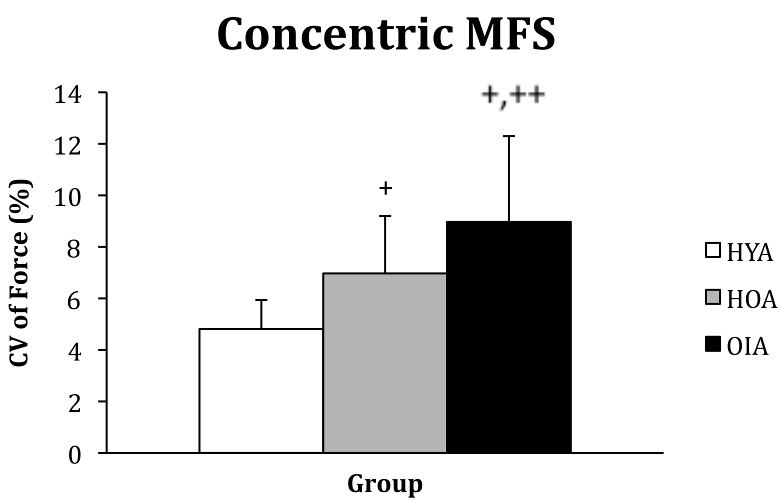


Figure 3.1 – Graphic illustration of MFS measurement. The force trace (small insert) represents an MFS trial over a 4 second time interval recorded during a muscle contraction (either CON or ECC). The enlarged illustration represents the middle 2 second interval used, between 60° to 30° of knee flexion, to calculate MFS expressed as the CV of Force.

A)



B)

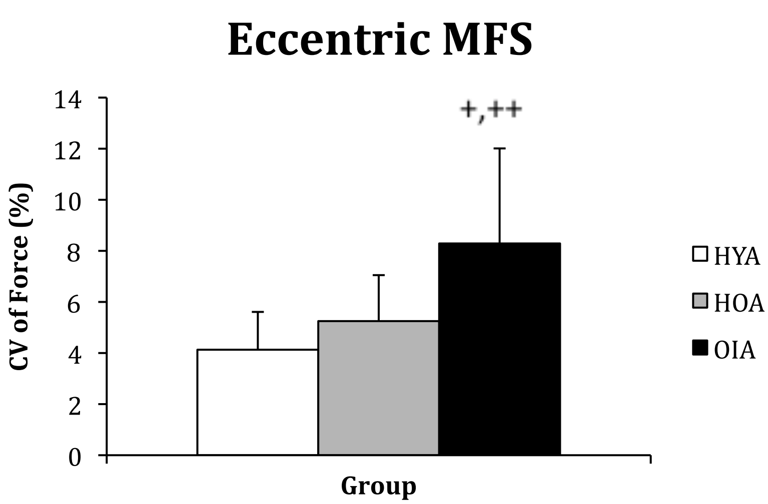


Figure 3.2 Group means of concentric and eccentric steadiness with a target force of 50% MVIC of the weaker lower extremity. A) Depicts CON MFS. B) Depicts ECC MFS

MFS measures (expressed as CV) are group means ± SD
+ = Significant difference when compared to HYA ($p < 0.05$)
++ = Significant difference when compared to HOA ($p < 0.05$)

Table 3.1 – Participant characteristics of healthy young, healthy old and old impaired adults who have fallen

Participant Characteristics	Healthy Young Adults	Healthy Old Adults	Old Impaired Adults Fallers
Mean Age (yrs)	24.4 ± 3.5	70.6 ± 3.7*	77.5 ± 7.0*,**
Height (cm)	176.0 ± 11.9	176.2 ± 8.8	166.4 ± 8.8*,**
Weight (kg)	77.0 ± 20.8	85.8 ± 13.3	69.5 ± 16.1**
BMI (Kg/M^2)	24.6 ± 4.7	27.6 ± 3.1	25.14 ± 6.0
MVIC (N)	463 ± 145	382 ± 82*	272 ± 68*,**

Values are group means ± SD, n=20 per group
*Significant difference (p< 0.05) with HYA
**Significant difference (p< 0.05) with HOA

Table 3.2 – Group means of concentric and eccentric steadiness with 95% CI

Group	CON MFS	95% C.I.	ECC MFS	95% C.I.
HYA	4.81 ± 1.12	[4.28, 5.34]	4.13 ± 1.48	[3.44, 4.83]
HOA	6.99 ± 2.23^{+}	[5.95, 8.03]	5.25 ± 1.80	[4.29, 6.21]
OIA	8.97 ± 3.32$^{+,++}$	[7.41, 10.53]	8.29 ± 3.72$^{+,++}$	[6.31,10.27]

MFS measures (expressed as CV) are group means ± SD and 95% C.I.
+ = Significant difference when compared to HYA (p< 0.05)
++ = Significant difference when compared to HOA (p< 0.05)

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CHAPTER 4

THE ASSOCIATION BETWEEN KNEE EXTENSOR FORCE STEADINESS, FORCE ACCURACY AND FUNCTIONAL MOBILITY IN OLDER ADULTS WHO HAVE FALLEN

Introduction

Older adults often experience muscle dysfunction, locomotor deficits, and mobility challenges that place them at an increased risk for falling (Delbaere, 2003; Galganski, Fuglevand, & Enoka, 1993; Rubenstein, 2006; Schiffman, Luchies, Richards, & Zebas, 2002; Shumway-Cook, Brauer, & Woollacott, 2000). Further, the ability for older adults to perform functional tasks such as walking, ascending or descending stairs or rising from a chair may require increased effort compared to young adults and could result in an accident (Hortobagyi, Mizelle, Beam, & DeVita, 2003). Specifically, a fall can occur when negotiating stairs, with greater incidences occurring during stair descent (Tinetti, Speechley, & Ginter, 1988). Submaximal muscle function has also been suggested as a potential contributor to falling risks (Carville, Perry, Rutherford, Smith, & Newham, 2007). It is not clear, however, if the ability to control submaximal force is directly linked to performance on mobility tasks in older adults at higher risk for falling.

The force produced during a muscle contraction fluctuates around an average value (Christou & Carlton, 2002; Enoka et al., 2003; Galganski et al., 1993; Krishnan, Allen, & Williams, 2011; Tracy, Byrnes, & Enoka, 2004). The amplitude of force fluctuations can provide information about the ability of the nervous system to regulate force output. The force fluctuations, or variability in motor output often characterized as muscle force steadiness (MFS), during submaximal muscle contractions is increased for older adults compared with young adults (Christou, 2011; Enoka et al., 2003; Hortobagyi, Tunnel, Moody, Beam, & DeVita, 2001; Laidlaw, Kornatz, Keen, Suzuki, & Enoka, 1999; Marmon, Pascoe, Schwartz, & Enoka, 2010). Further, some have speculated that increased motor variability may adversely impact movement precision depending on the type of muscle contraction or age of the individual (Burnett, Laidlaw, & Enoka, 2000; Christou, Shinohara, & Enoka, 2003; Enoka et al., 2003; Galganski et al., 1993; Kornatz, Christou, & Enoka, 2005; Laidlaw, Bilodeau, & Enoka, 2000).

In addition to MFS, muscle force accuracy (MFA), which measures the ability of an individual to achieve a target force for a period of time, has also been utilized to assess the control of submaximal force output (Hortobagyi et al., 2001). Although data on MFA are limited and relatively infrequently reported compared with MFS, MFA has been found to be impaired in older adults during relatively slow contractions and rapid, discrete contractions (Christou, Poston, Enoka, & Enoka, 2007; Christou et al., 2003; Hortobagyi, Garry, Holbert, & Devita, 2004; Hortobagyi et al., 2001). It is not known whether MFA is associated with decreased mobility in older adults who have fallen. It may seem intuitive that increased variability in motor output, characterized as MFS and MFA, may be associated with decreased functional mobility in older adults who have fallen. However, to the best of our knowledge, no evidence has been reported in that population.

Thus, the purpose of this study was to determine the association between concentric and eccentric submaximal motor control of the knee extensors and the performance of mobility tasks in older adults who have fallen. We postulate that MFS and MFA during concentric (CON) and eccentric (ECC) knee extensor contractions may be linked to functional mobility.

Methods

Twenty older impaired adults (OIA) volunteered to participate in a 1 day experimental session lasting approximately 2.5 hours. The OIA participants included adults ≥65 years of age who had experienced at least 1 unintentional fall in the past year, were able to ambulate within the community with or without an assistive device and were managing two or more co-morbid medical conditions. Exclusion criteria included individuals with progressive neurologic disorders, undergoing treatment for cancer, chronic heart failure or unstable medical conditions. Participants were recruited from the Salt Lake City, Utah community. Participants provided signed confirmation of their informed consent. The Institutional Review Board at the University of Utah approved the procedures used in this study.

Knee Extension Maximal Muscle Torque Measurements

Participants performed maximal voluntary isometric contractions (MVIC) of the knee extensor muscles at a joint angle of 45° of knee flexion on a KinCom dynamometer (KinCom 500H, Chattecx Corp; Harrison, TN). The participants were in a seated position with the hips flexed to 80° and the knees flexed to 90°. The center of the knee joint was aligned with the axis of the dynamometer, the midthigh was secured with a strap, and the distal lower leg was secured to the lever arm with a velcro strap. Prior to testing, participants performed three submaximal contractions at approximately 50% effort. Following a rest period of 1 to 3 minutes, participants performed three maximal isometric contractions by pushing as forcefully as they possibly could for 3 seconds, with strong verbal encouragement. A 1 minute rest period was given between each trial. The maximal peak torque of the three trials, with a difference no greater than 5% between the three trials, was used as the MVIC. A fourth trial was performed if the aforementioned criteria were not met. Following MVIC testing and prior to measuring MFS, participants were given a 10 minute rest period.

Muscle Force Steadiness and Muscle Force Accuracy

MFS was measured by having the participants exert submaximal CON and ECC contractions of the knee extensors to match a target line of 50% of their MVIC on the KinCom dynamometer (KinCom 500H, Chattecx Corp; Harrison, TN). The participant's force was represented as a left-to-right scrolling line on the computer monitor. The monitor was positioned approximately 1 meter in front of the participant. Participants were instructed to perform the smoothest, most steady contraction they possibly could while attempting to match the target force line.

The dynamometer speed was set at 15 deg•sec-1 and data were collected over a total range of motion of 60° (75 -15° of knee flexion). Participants initially performed two familiarization trials followed by a series of test trial sequences (TTS), with each series containing three trials per TTS for a total of 30 trials. Each trial lasted 8 seconds in duration consisting first of a 4 second CON contraction followed by a 4 second ECC contraction of the knee extensor muscles. Participants were given a 1 minute rest period between each test trial and a 3 to 5 minute rest period between each series of three trials.

The first six TTS (a total of 18 trials) were not included in the data analysis as they were considered practice trials to ensure that participants understood the task, and to avoid the potential contribution of early motor learning effects as reported by some (Hortobagyi et al., 2001; Sorensen et al., 2011). MFS was characterized by the coefficient of variation (CV=SD/mean•100), an accepted method for quantifying normalized force variability (Galganski et al., 1993; Tracy & Enoka, 2002). MFA was defined as the difference between the average force produced and the submaximal target force (Figure 4.1).

Mobility Testing

Standardized tests of functional mobility were used: the 6-minute walk (6MW), the timed up and go test (TUG), and the stair test (ascent = StA and descent = StD). These tests have been reported to be reliable via intraclass correlation coefficient (ICC range 0.90-0.96) in older adults (Crosbie, Naylor, & Harmer, 2010; Shumway-Cook et al., 2000; Steffen, Hacker, & Mollinger, 2002).

Six-Minute Walk

The 6MW test was administered by having the participants walk as far as possible in 6 minutes. The test course was a rectangular, tiled corridor 90 meters in total length. The timing of participants commenced once movement occurred and ceased following 6 minutes of elapsed time. The total distance walked in meters (m) was used for data analysis.

The Timed Up and Go Test

The TUG test began with participants seated with their backs against the backrest of a chair (43 centimeter seat height). The participants were instructed to rise from the chair as quickly and safely as they could, walk a distance of 3 meters, turn around a cone, and walk back to the chair and sit back down. Timing commenced once movement occurred and ceased when participants returned to the starting position with their backs against the backrest of the chair. Participants were given one practice trial, followed by three test trials, with at least a 1 minute rest period between trials. The average of three trials was used for data analysis.

Stair Test

The StA was administered by having the participants positioned at the base of a well lit 10 step (17.15 centimeter steps) staircase with handrails. Under close supervision, the participants were instructed to safely ascend the stairs as quickly as possible. Timing commenced once movement occurred and stopped when both feet reached the top step. Participants were given 1 to 3 minutes rest between trials. The average of three trials was used for data analysis.

The StD was then administered by having the participants descend the same flight of stairs, under close supervision, as quickly and safely as possible. The timing commenced once movement occurred and was terminated when both feet reached the base of the flight of stairs. Participants were given 1 to 3 minutes rest between trials. The average of three trials was used for data analysis.

Data Processing

The torque signal from the dynamometer was analog-to-digital converted at 1000 samples per second (DAQ-National Instruments) and low-pass filtered (20th order Butterworth) at 100 Hz. The middle 2 seconds from each 4 second force trace was used to measure MFS to avoid the ramping up and down of force production. After linear detrending of the middle 2 seconds, the mean torque, the standard deviation and CV were calculated using Matlab software (Mathworks, Inc.; Natlick, MA, Matlab 2009). MFS test trials where the mean torque produced was within ± 20% of the target force were included as part of the data analysis. MFA was expressed as a percentage of the target force (%TF). The mean force produced was divided by the target force and multiplied by 100 ([mean force* target force-1]*100). A value of 100%TF meant that the mean force was equal to the target force. MFA %TF that was above or below the 100% level was indicative of overshooting or undershooting of the mean force relative to the target force.

Statistical Analysis

The primary purpose of this study was to determine whether a relationship existed between the control of submaximal motor output of the knee extensors, characterized as MFS and MFA, and mobility tasks such as the 6MW, TUG, StA and StD in older adults who have fallen. Pearson product moment correlation coefficients were utilized to evaluate the bivariate relationships between MFS and MFA during CON or ECC and the scores for the 6MW, TUG, SCT tests. The statistical significance level was set at $p<0.05$. statistical package for the social sciences (SPSS) version 20 was used for data analysis (IBM SPSS Inc, Armonk, NY).

Results

Participant characteristics are included for age, gender, height, weight, BMI and MVIC in Table 4.1.

Muscle Force Steadiness and Functional Mobility Tests

No significant correlations were detected for CON MFS and functional mobility tasks: 6MW (r=-0.22, p=0.93); TUG (r=-0.13, p=0.96); StA (r=-0.14, p=0.55); and StD (r=0.02, p=0.93). Likewise, ECC MFS was not significantly correlated with functional mobility tasks consisting of the: 6MW (r=-0.39, p=0.09); TUG (r=0.42, p=0.07); StA (r=0.27, p=0.24); and StD (r=0.30, p=0.20).

Muscle Force Accuracy and Functional Mobility Tests

Although CON MFA was not correlated with functional mobility tasks: 6MW (r=-0.10, p=0.67); TUG (r=0.23, p=0.33); StA (r=0.17, p=0.47); and StD (r=0.38, p=0.10); there were moderate to strong correlations for ECC MFA: 6MW (r=-0.48, p<0.05); TUG (r=0.68, p<0.01); StA (r=0.60, p<0.01); and StD (r=0.75, p<0.01) (Figure 4.2).

Discussion

The purpose of this study was to determine if the steadiness and accuracy of submaximal knee extensor force was correlated with performance on mobility tasks in older adults who had fallen. Interestingly, only force accuracy during ECC contractions was correlated with performance on mobility tasks. The ECC MFA explained between ~23-56% of the variance in the performance of the mobility tasks. However, no statistically significant associations were demonstrated between MFS during either CON or ECC contractions and mobility performance. In addition, there was no correlation between MFA during CON contractions and mobility performance. These findings are novel and unique in that: 1) this is the first report to document MFA as a feature of submaximal muscle function linked to mobility tasks; 2) this is the first study to show that this relationship is specific to submaximal ECC contractions; and 3) these relationships may point to an important feature of muscle impairment for older adults at risk for falling.

Previously reported evidence regarding MFA that is relevant to the findings of this study is very limited. The only reported evidence that examined submaximal force control as a correlate with mobility performance is from Seynnes et al. (2005) who reported that isometric MFS was associated with chair rise time, yet no associations were detected between MFA and functional mobility tasks (Seynnes et al., 2005). Hortobagyi et al. did not correlate motor control measures (MFS and MFA) to functional tasks (Hortobagyi et al., 2001). However, they did report that older adults demonstrated overshooting of the target force by twice the amount during CON and three times the amount during ECC contractions of the knee extensor muscles compared to young adults. Moreover, although Carville et al. (2007) did not explicitly link steadiness measures with functional mobility, they did report that at-risk older adults who had fallen demonstrated greater variability in motor output during eccentric contractions but not concentric knee extensor contractions when compared with older nonfallers (Carville et al., 2007). Collectively, the reported evidence of associations between knee extensor steadiness and accuracy (MFS and MFA) and mobility tasks is very limited and varies between contraction types.

Interestingly, others have compared steadiness and accuracy in older adults with performance tasks that have included either general limb movement trajectories or motor tasks that require movement precision (Kornatz et al., 2005; Marmon et al., 2010). In general, reported evidence regarding MFS and aging suggests that older adults demonstrate greater force variability when performing submaximal muscle contractions compared to young adults (Burnett et al., 2000; Christou et al., 2003; Galganski et al., 1993; Graves, Kornatz, & Enoka, 2000; Tracy & Enoka, 2002). Further, older adults often demonstrate greater motor variability particularly when performing ECC contractions compared with CON or isometric contractions, particularly at low target force levels (Enoka et al., 2003; Hortobagyi et al., 2001; Laidlaw et al., 2000; Tracy, Maluf, Stephenson, Hunter, & Enoka, 2005). For example, when older adults perform finger abduction with the first dorsal interosseus muscle of the hand, they tend to demonstrate greater force variability output during ECC compared to CON contractions (Burnett et al., 2000; Christou et al., 2003; Kornatz et al., 2005; Laidlaw et al., 2000). Interestingly, Marmon et al. (2010) investigated steadiness in muscles of the hand (abduction of the index finger, and pinch between thumb and index finger) and their relationship to performing four tasks that were used to assess fine motor function in young, middle aged, and old adults (Marmon et al., 2010). Older adults were less steady than the young or middle aged adults with both steadiness tasks. Further, moderate correlations were detected between isometric steadiness and two of the four tasks in older adults. Additionally, when considering limb movements that utilized either the elbow flexors or the knee extensors, similar findings to those mentioned previously were reported, that older adults demonstrated greater variability when performing ECC contractions compared to CON contractions (Carville et al., 2007; Graves et al., 2000; Hortobagyi et al., 2001). Collectively, the reported evidence of increased force variability in older adults appears to be present whether performing precise motor tasks in the hand, general limb trajectories or varying types of muscle contractions. Further, the relationships between task performance, movement precision and steadiness may present additional challenges for older adults who have fallen (Christou & Carlton, 2002; Hortobagyi & DeVita, 1999; Seynnes et al., 2005).

Possible Mechanisms

It may be that unique characteristics or variations in the descending command are prevalent during ECC contractions compared with CON or isometric contractions. For example, reviews by Enoka (1996), Duchateau and Enoka (2008), and Duchateau and Baudry (2013) have suggested plausible mechanisms regarding how the motor output or descending command may vary when performing ECC compared to CON contractions.

In general, when a CON contraction is performed, the torque produced by the muscle force produced is slightly greater than the torque produced by the applied load in order for the muscle to produce a shortening contraction. However, during an ECC contraction, the applied load torque is greater than the muscle force torque and the muscle performs a lengthening contraction (Duchateau & Enoka, 2008; Enoka, 1996). Given these parameters, the muscle activation levels during submaximal ECC contractions may differ from that of CON contractions and the specific modulation of the activation signal to the targeted muscle may vary (Enoka et al., 2003; Mottram, Christou, Meyer, & Enoka, 2005). For example, during an ECC contraction, reported evidence suggests that in addition to derecruitment of active motor units, the discharge rate also tends to decline (Nardone, Romano, & Schieppati, 1989). Accordingly, the overall activation level of a muscle is less during ECC contractions compared to CON (Enoka, 1996). Further, changes in the neuromuscular system due to aging include reductions in the number of motor neurons and muscle fibers, motor unit remodeling via collateral sprouting from adjacent motor neurons, and increased size of existing motor units (Roos, Rice, & Vandervoort, 1997; Vandervoort, 2002). Collectively, these age related changes to the motor unit can affect the activation and discharge rate of the motor units, thereby contributing to the variability in the force output (Christou, 2011; Enoka et al., 2003; Galganski et al., 1993).

An additional mechanism that may also play a contributory role to the increased variability in motor output is presynaptic inhibition of Ia afferents. Briefly, input from Ia afferents to the active motor neuron pool can be inhibited due to the depolarization of primary afferent fibers by interneurons and consequently affect the activation of the motor units to the targeted muscle (Baudry, Maerz, & Enoka, 2009; Baudry, Maerz, Gould, & Enoka, 2010). Further, depending on the task that is to be performed, be it position control or force control, older adults demonstrated a decreased ability to regulate presynaptic inhibition compared to young adults. For example, Baudry et al. (2009) reported that the ability of older adults to regulate presynaptic Ia afferent inhibition was reduced when individuals were tasked to control hand position while supporting a mass (position control) compared with exerting the same force (force control) against a rigid constraint (Baudry et al., 2009).

The clinical relevance of the reported findings in this study are such that MFA may be an additional factor to consider when exploring force control in older adults, particularly in those who have fallen, and this may impede or reduce their ability when performing functional mobility tasks. Since resistance exercise training can improve MFS in older adults (Doherty, 2003; Hortobagyi et al., 2001; Kornatz et al., 2005;

Laidlaw et al., 1999; Tracy et al., 2004), further investigation is warranted on the effects of such training on MFA measures, particularly when performing ECC contractions.

Limitations

This study included a relatively small number of individuals and performed multiple bivariate correlations. Therefore, the results of this study should be interpreted with caution, as statistical associations between ECC MFA and functional mobility tasks does not equate to causation. For example, discretion should be used with interpreting these outcomes when designing interventions for improving force control in older adults who have fallen. However, these findings are novel and possibly suggest that during lengthening contractions, inaccurate submaximal force output may contribute to impaired mobility in older adults at risk for falling.

Conclusion

Overall, there were moderate to strong correlations between the ability to produce accurate force during eccentric contractions and performance on functional mobility tasks in older adults who fall. These findings are novel and suggest that an inability to regulate eccentric forces may contribute to impaired mobility in older adults at high risk for falling. Further investigations should determine if training-related improvements in force accuracy during lengthening contractions result in improved functional mobility in older adults at risk for falls.

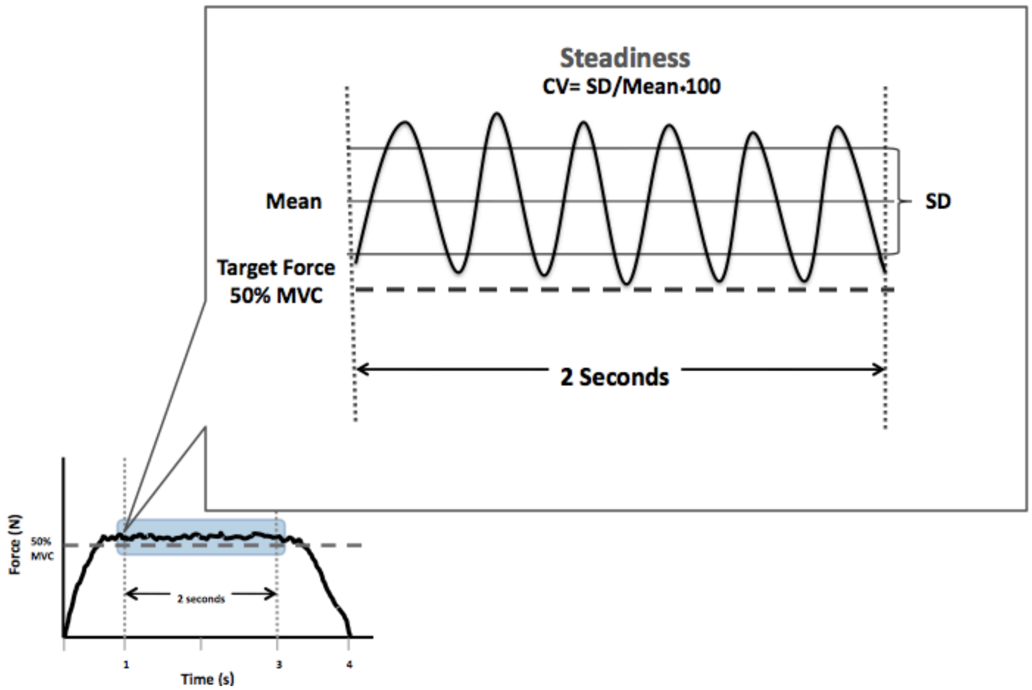
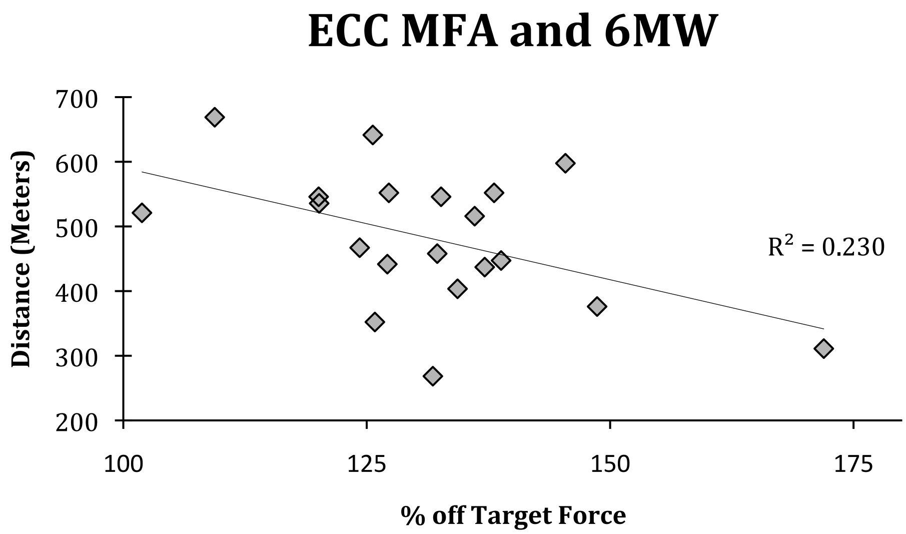
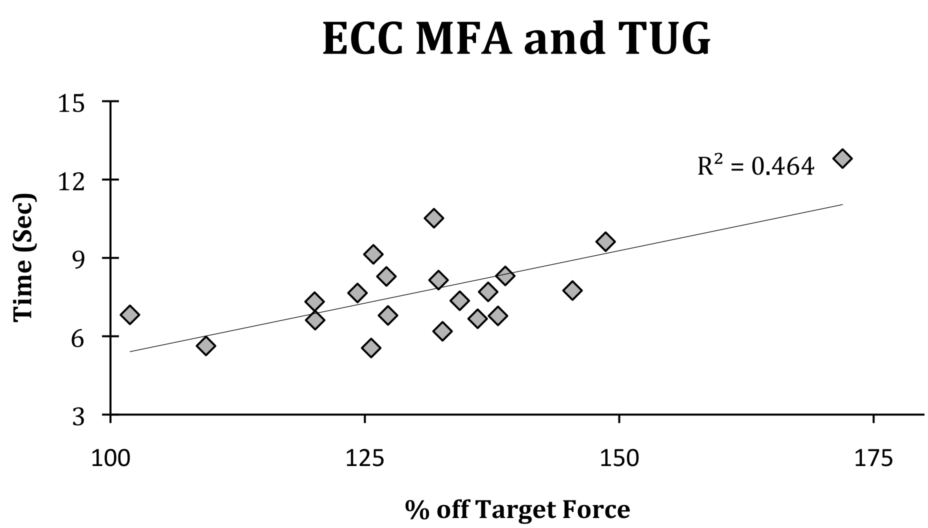


Figure 4.1 – The force trace represents an MFS trial over a 4 second time interval recorded during a muscle contraction (either ECC or CON). MFA was also recorded as the force output relative to a target force set as 50% of the participant's MVIC. The middle 2 second interval (enlarged) was used to calculate MFS expressed as CV of force, and MFA.

A)

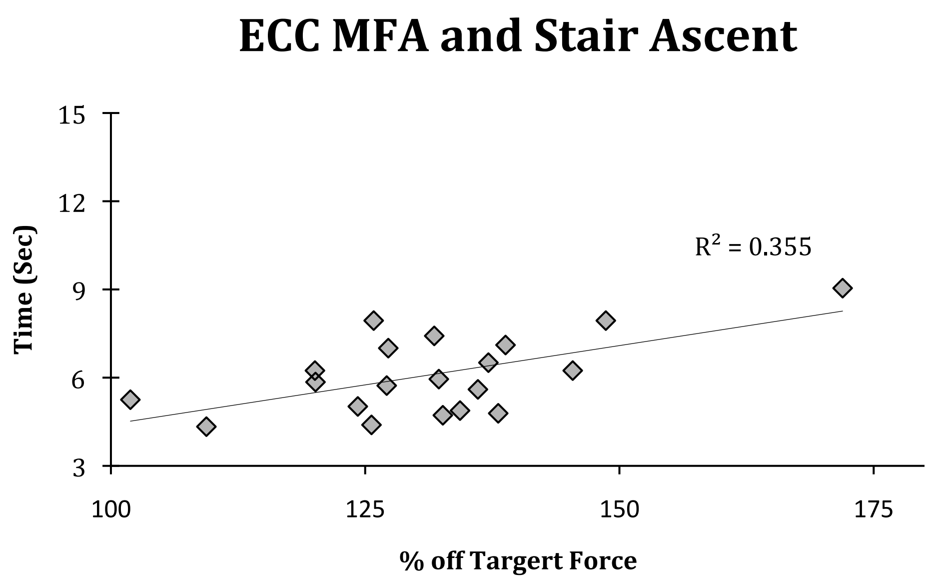


B)

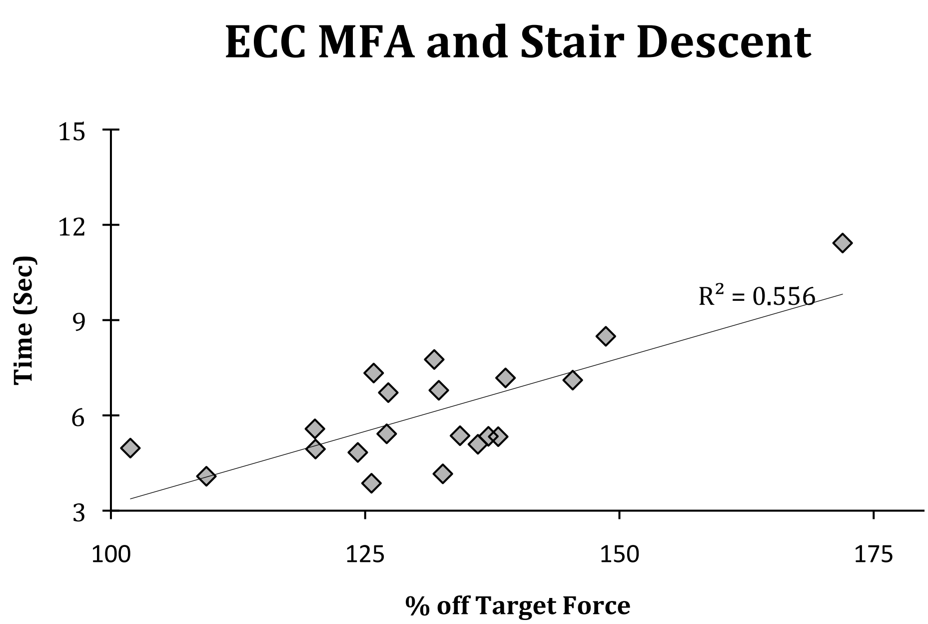


Figures 4.2 Represents moderate to strong relationships between eccentric MFA (expressed as the percentage of target force) and functional mobility test scores. A) MFA and 6MW r = -0.48, p<0.05; B) MFA and TUG r = 0.68, p<0.01; C) MFA and stair ascent r = 0.60, p<0.01; D) MFA and stair descent r = 0.75, p<0.01.

C)



D)



Figures 4.2 Continued.

Table 4.1 – Participant characteristics of older impaired adults who had fallen

Participant Characteristics	**Older Impaired Adults**
Mean Age (yrs) ± SD	77.5 ± 7.0
Height (cm) ± SD	166.4 ± 8.8
Weight (kg) ± SD	69.5 ± 16.1
BMI (Kg/M^2) ± SD	25.14 ± 6.0
MVIC (N) ± SD	272 ± 68

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CHAPTER 5

RESISTANCE TRAINING IMPROVES STEADINESS AND ACCURACY OF KNEE EXTENSOR FORCE IN OLDER FALLERS

Introduction

The neuromuscular system undergoes age-related changes that can negatively affect muscle function (Christou, Shinohara, & Enoka, 2003; Delbaere, 2003). Suboptimal control of muscle force can adversely impact the ability of older adults to perform daily mobility-related tasks such as rising from a chair, ascending and descending stairs or walking (Hortobagyi, Mizelle, Beam, & DeVita, 2003). Further, when a muscle is activated by the nervous system the force produced does not remain constant but tends to fluctuate, a feature termed muscle force steadiness (MFS), around an average value (Christou & Carlton, 2001; Enoka et al., 2003; Tracy & Enoka, 2002). Variability in force output, referred to as muscle force accuracy (MFA), can also influence the ability of an individual to achieve or maintain a desired force (Delbaere, 2003; Hortobagyi, Tunnel, Moody, Beam, & DeVita, 2001). The ability to sustain steady and accurate motor output and movement is often degraded in older adults, particularly when performing submaximal lengthening or eccentric muscle contractions (Delbaere, 2003; Hortobagyi & DeVita, 1999; Kornatz, Christou, & Enoka, 2005; Larsen, Sorensen, Puggaard, & Aagaard, 2009; Seynnes et al., 2005). Impaired control of eccentric MFS in older adults has been linked to an increased risk for falling, especially during eccentric dependent tasks like descending stairs or ramped declines (Carville, Perry, Rutherford, Smith, & Newham, 2007; Hortobagyi et al., 2003; Mian, Thom, Narici, & Baltzopoulos, 2007; Rubenstein, 2006; Shumway-Cook, Brauer, & Woollacott, 2000).

Resistance exercise training can improve maximal muscle force output, e.g. muscle strength. Submaximal MFS has also been reported to improve following resistance exercise by some, but not all (Beck, Defreitas, Stock, & Dillon, 2011; Doherty, 2003; Hortobagyi et al., 2001; Kornatz et al., 2005; Laidlaw, Kornatz, Keen, Suzuki, & Enoka, 1999; Tracy, Byrnes, & Enoka, 2004). Multicomponent exercise fall reduction programs designed to improve mobility in older adults who have fallen often incorporate resistance exercises (Beck et al., 2011; Shumway-Cook, Gruber, Baldwin, & Liao, 1997). However, it is not known whether resistance exercise incorporated into a multicomponent exercise fall reduction program improves MFS or MFA in this impaired population. Interestingly, resistance exercise via negative eccentric work (RENEW) has also been reported to be effective in improving muscle strength and reducing fall risk, as individuals are able to produce high force levels at low metabolic costs compared to standard or traditional modes of resistance training (Dibble, Hale, Marcus, Gerber, & LaStayo, 2009; LaStayo, Marcus, Dibble, Smith, & Beck, 2011; LaStayo et al., 2009; LaStayo et al., 2003; Marcus, Lastayo, Dibble, Hill, & McClain, 2009). It is not known whether resistance training utilizing RENEW is effective in improving MFS or MFA in older adults who have fallen.

Thus, the purpose of this study is to determine if, as part of a multicomponent fall reduction program, resistance training utilizing either a traditional resistance exercise program (TRAD) or RENEW improves MFS or MFA of the knee extensor muscles in older adults who have fallen. It is hypothesized that both groups will experience improved control of force output following 12 weeks of resistance training. However, improvements in MFS and MFA, particularly during eccentric contractions, may be greater with RENEW than TRAD.

Methods

Seventy-two older adults ≥65 years of age ($\bar{x}$ = 76 ± 7 years, males=23, females=49), who experienced an unintentional fall to the ground in the past year, volunteered to participate in this randomized multicomponent exercise fall reduction study. A block randomization process was used for assigning participants into either the TRAD or RENEW groups (see Figure 5.1) to prevent an imbalance between the proportions of females to males and to facilitate similar numbers of participants within the two groups, respectively. Participants were ambulatory within the community with or without an assistive device. All participants were required to have two or more co-morbid conditions yet were medically able to participate in a multicomponent exercise program. Written informed consent was obtained and the Institutional Review Board at the University of Utah approved the procedures used within this study. Exclusion criteria included individuals with progressive neurological disorders, active cancer, chronic heart failure or unstable medical conditions.

Knee Extension Maximal Muscle Strength Measurements

Maximal voluntary isometric contraction (MVIC) knee extensor muscle strength was measured at a joint angle of 45° of knee flexion on a KinCom dynamometer (KinCom 500H, Chattecx Corp; Harrison, TN). Participants were positioned on the dynamometer seat with the center of the knee joint aligned with the axis of the dynamometer's shaft. The participants midthigh region was stabilized with a nylon strap and the distal lower leg was secured to the dynamometer lever arm with a velcro strap. Participants initially performed three submaximal trials during a familiarization period. Following a rest period of 1 to 3 minutes, participants performed three MVIC efforts. A 1 minute rest period was given between each test trial. MVIC was tested on each lower extremity. The maximal peak strength of the three trials, the average difference being no greater than 5% between the three trials, was used as the MVIC muscle strength value. If this was not obtained, a fourth trial was performed.

Muscle Force Steadiness and Muscle Force Accuracy

MFS was measured by having the participants exert submaximal CON and ECC contractions of the knee extensors to match a target line representing 50% of their MVIC using a KinCom dynamometer. As participants applied force to the lever arm, a horizontally scrolling line was produced on the computer monitor. The monitor was positioned approximately 1 meter in front of the participants. Participants were instructed to perform the smoothest, most steady contraction they possibly could while attempting to match the target force line.

The dynamometer speed was set at 15 degrees*second-1 and data were collected over a 60° range of motion (75 -15° of knee flexion). Participants performed two practice trials followed by three test trials. Each trial lasted 8 seconds, 4 seconds for CON and 4 seconds for ECC. Participants were given a 1 minute rest period between each test trial. MFS was characterized as the coefficient of variation (CV), calculated as the standard deviation (SD) divided by the mean, multiplied by 100 (SD/Mean * 100).

MFA was also measured and was calculated as the difference between the average force produced and the submaximal target force. MFS and MFA were measured on the weaker of the two lower extremities.

Multicomponent Exercise Fall Reduction Program and Resistance Training

Participants trained three times per week for 12 weeks as part of a multicomponent exercise fall reduction program. Training sessions consisted of aerobic activity, flexibility exercises, static and dynamic balance training, and upper and lower extremity exercises with resistance. The TRAD group performed 3 sets of 15 repetitions of a seated bilateral leg press exercise (Tuff Stuff PS -230 Deluxe Leg Press, Tuffstuff, Chino, CA) at 60-65% of their one repetition maximum (RM) for the initial 2 weeks. Training sessions for the remaining 10 weeks were performed at 70% of 1 RM, which was assessed every 2 weeks thereafter (see Table 5.1). In addition, the TRAD group performed standing multidirectional straight leg exercises with a weighted cuff placed just proximal to the ankle. The training loads for this exercise were increased as tolerated every 2 weeks provided the participants could complete 3 sets of 15 repetitions. The RENEW group performed a progressive resistive eccentric exercise of the knee and hip extensor muscles using a recumbent ergometer (Eccentron, Baltimore Therapeutic Equipment, Hanover, MD). The pedal speed ranged between 12 to 18 revolutions per minute. Visual feedback of the work performed for each revolution was displayed on a computer monitor (see Figure 5.2). Participants performed eccentric work from approximately 15-75° of knee flexion. Perceived exertion was assessed with the Borg rating scale between 6 and 20 (Noble, Borg, Jacobs, Ceci, & Kaiser, 1983). In the first week of RENEW, sessions lasted 3 to 5 minutes and were performed at a very, very light intensity. During subsequent weekly training sessions, participants were gradually allowed to progress from a fairly light, to a somewhat hard intensity level, with the duration of each session being progressively increased to a maximal 15 minute duration of RENEW (Table 5.2).

Data Processing

The analog torque signal from the dynamometer was converted via a digital processor (DAQ-National Instruments), and low pass filtered at 100 Hz. Customized software was used to collect the data (National Instruments, Labview version 8.6) during test trials. The middle 2 seconds from each 4 second force segment was used to measure MFS and MFA to avoid the transient ramping of force during acquisition of the target force. After linear detrending, the mean force, standard deviation (SD) of force, and coefficient of variation (CV) of force were calculated for each of the trials using Matlab software (Mathworks, Inc.; Natlick, MA, Matlab 2009). The CV of force was taken as a measure of the variability, or steadiness of muscle force (MFS). The mean CV of the three trials was calculated as the outcome measure. The accuracy of force was represented by MFA, the difference between the mean force and the target force, and expressed as a percentage of the target force (%TF). The mean force of the three trials was averaged, then divided by the target force and multiplied by 100 ([mean force x target force-1] x100), with 100%TF meaning the mean force was equal to the target force. MFA results that were above or below the 100%TF were indicative of overshooting or undershooting of the mean force relative to the target force.

Statistical Analysis

To determine whether resistance training with TRAD or RENEW improves MFS or MFA, separate two-way analyses of variance, for CON and ECC contractions were conducted to determine differences between groups (TRAD vs RENEW) and across time (pre training and 12 weeks posttraining) as the main effects, and treatment group by time as the interaction effect. If a significant interaction was detected, post hoc comparisons were used to determine specific effects utilizing a bonferroni correction for multiple comparisons. The data were analyzed using statistical package for the social sciences (SPSS) version 20 (SPSS Inc, Chicago, IL). The *p*-value for all statistical tests was set at 0.05.

Results

Age (TRAD = 76.2 ± 6.4 yrs, RENEW = 75.2 ± 6.0 yrs), height (TRAD = 167.4 ± 8.1 centimeters, RENEW = 167.5 ± 10.3 centimeters), weight (TRAD = 78.4 ± 17.6 kilograms, RENEW = 76.8 ± 15.1 kilograms), BMI (TRAD = 27.9 ± 6.0 kg/m2, RENEW = (27.4 ± 4.9 kg/m2) and gender (TRAD = 11 M, 25 F, RENEW = 10 M, 22 F) distributions did not differ between the groups ($p>0.05$). Initial knee extensor MVIC strength measures (TRAD 269 ± 82 N, RENEW 295 ± 98 N), and post-12 weeks of resistance exercise training (299 ± 92 N and 305 ± 100 N) were recorded, respectively. A total of 12 participants did not complete the present study, 4 participants in the TRAD group (3 for personal reasons, and 1 completed the training but did not return for posttesting), and 8 participants in the RENEW group (2 for personal reasons, 4 did not complete the training, and 2 completed the training but did not return for posttesting).

Muscle Force Steadiness

A significant main effect for time occurred for both ECC (*F*(1,66)=28.73, $p<0.01$), and CON (*F*(1,66)=19.21, $p<0.01$) MFS (see Figure 5.3A & 5.3B). There were no significant main effects detected between groups (ECC (*F*(1,66)=2.11, $p=0.15$); CON (*F*(1,66)=3.32, $p=0.07$), nor was there a group by time interaction effect (ECC (*F*(1,66)=0.60, $p=0.44$); CON (*F*(1,66)=0.67, $p=0.42$). The CV of force for CON contractions decreased by 23% and 28% for the TRAD and RENEW groups. Likewise, the CV of force for ECC contractions decreased by 25% and 28% for the TRAD and RENEW groups, respectively. The magnitude of improvement experienced by each group, for each contraction type following 12 weeks of training were significant ($P < 0.01$) (see Table 5.3).

Muscle Force Accuracy

As can be seen in Figure 5.4A & 5.4B, a significant main effect for time occurred for MFA only during ECC contractions (ECC (*F*(1,66)=22.52, $p<0.01$); CON (*F*(1,66)=0.01, $p=0.93$). No significant group effects were detected for ECC (*F*(1,66)=0.001, $p=0.97$) or CON (*F*(1,66)=0.61, $p<0.44$). Further, there was no group by time interaction effect for either contraction type (ECC (*F*(1,66)=0.10, $p=0.75$); CON (*F*(1,66)=0.36, $p=0.55$). Target force accuracy, expressed as a percentage of the target force (%TF), for ECC MFA improved by 11% and 14% for the TRAD and RENEW groups, respectively.

The improvement in the percent change of target force accuracy experienced by each group for ECC contractions following 12 weeks of training were significant ($p< 0.01$); (see Table 5.4). Note that CON MFA was good prior to resistance exercise training, whereas ECC MFA was less accurate as the participants tended to overshoot the target force. Resistance exercise training only partially corrected ECC inaccuracy.

Discussion

The purpose of this study was to determine whether resistance training of the lower extremities utilizing either traditional resistance training or eccentrically biased resistance training (TRAD or RENEW) as part of a multicomponent exercise fall reduction program could improve the steadiness and accuracy of knee extensor force in older fallers. The main findings of the present study were: 1) significant improvements in MFS for both CON and ECC muscle contractions after training with no evidence of greater adaptations for TRAD or RENEW; and 2) significant improvements in MFA only during ECC muscle contractions after training, again with no evidence for differences between TRAD and RENEW.

These findings are unique in that the effects of resistance exercise training on the control of submaximal muscle force output was tested in a population of older fallers enrolled in a rehabilitation program. Previous investigations demonstrated resistance exercise training to be effective in improving MFS though they were conducted with healthy older adults. Interestingly, the findings of the present study with an at-risk older adult population were in agreement with what has previously been reported in healthy old adults. For example, some investigators have reported that resistance exercise training in healthy older adults decreased the variability of MFS during CON and ECC contractions with the knee extensors, but not with isometric contractions (Beck et al., 2011; Hortobagyi et al., 2001; Manini, Clark, Tracy, Burke, & Ploutz-Snyder, 2005; Tracy et al., 2004; Tracy & Enoka, 2006). However, others have reported that resistance exercise training can improve isometric MFS of the knee extensors (Gault & Willems, 2013). Further, similar findings of improved MFS during isometric contractions following a resistance exercise training program were also reported with the first dorsal interosseus muscle of the hand, particularly at lower forces (Keen, Yue, & Enoka, 1994; Kornatz et al., 2005; Laidlaw et al., 1999). Others findings suggest that the greatest improvements in MFS after resistance training are observed in the participants who exhibit the greatest variability (worse impairment) before training, or for those with a neurological or musculoskeletal disorder (Beck et al., 2011; Manini et al., 2005; Tracy et al., 2004). Accordingly, the reported findings of improved MFS with resistance exercise training tend to be more apparent in elderly adults compared with young adults (Beck et al., 2011). The variability of muscle force differs between young and old adults, though the evidence is not always consistent and differs depending on the muscle or muscle group, type of muscle contraction, and contraction intensity (Enoka et al., 2003).

The improvements in MFA with resistance exercise training in the present study occurred only with ECC and not CON contractions. Prior to resistance exercise training, we observed that the ability of older fallers to maintain an accurate, submaximal force output at 50% MVIC were impaired compared with young adults, particularly during ECC contractions when they tended to exceed the submaximal target (Chung-Hoon, Marcus, Tracy, Dibble, & LaStayo, 2013). The effect that resistance exercise training has on improving MFA has received limited attention, though those studies that did compare MFA in healthy young and old adults also observed that older adults were less accurate in controlling submaximal force output and tended to overshoot the target force when performing ECC contractions with muscles in the knee and hand (Christou, Poston, Enoka, & Enoka, 2007; Hortobagyi et al., 2001; Seynnes et al., 2005). The findings of the present study are in agreement with what has previously been reported regarding MFA, and the results suggest that an impaired population of older fallers can respond favorably. Furthermore, since older fallers consistently overshot the submaximal target force, particularly when performing ECC contractions of the knee extensors, their ability to perform functional tasks might be impaired. For example, the impaired ability to accurately regulate ECC muscle contractions, particularly when performing functional tasks that require ECC contractions such as descending stairs may be challenging to older adults who have fallen and could potentially increase their fall risk (Carville et al., 2007; Galganski, Fuglevand, & Enoka, 1993; Hortobagyi & DeVita, 1999; Larsen et al., 2009; Seynnes et al., 2005). Taken collectively, MFS and MFA characterize the quality of submaximal force production and the observed findings in the present study demonstrate that impairments in force steadiness and force accuracy can be attenuated with resistance exercise training. Accordingly, this adaptation could be functionally beneficial to older adults during eccentrically-focused tasks such as stair descent (Hortobagyi et al., 2003; Seynnes et al., 2005; Tracy & Enoka, 2006).

The possible neural mechanisms which collectively may account for the improvements in MFS and MFA following 12 weeks of resistance training in older fallers could include changes in the variability of discharge rate of the motor units, alterations in the coactivation of antagonist muscles and altered presynaptic inhibition of the motor neurons.

The variability in the force produced can be attributed to differences in the motor units that are recruited and the rates at which these motor units discharge action potentials

(Duchateau, Semmler, & Enoka, 2006; Enoka et al., 2003). The quality of descending command to motor neurons may also vary when performing CON and ECC contractions (Duchateau & Enoka, 2008). The activation of the motor units may not be the same for ECC compared with CON contractions, i.e., a unique strategy between contraction types might exist since the discharge rate is less during ECC contractions (Duchateau & Baudry, 2013). Variability in the discharge rate of motor units tend to increase the variability of force, particularly during ECC contractions in older adults (Duchateau & Enoka, 2008). Resistance exercise training may be effective in altering the variability in the discharge rate of the recruited motor units in that the descending motor command may be modified thereby reducing the fluctuations in the net force produced (Enoka et al., 2003; Keen et al., 1994; Kornatz et al., 2005; Manini et al., 2005; Tracy et al., 2004). Further, the modulation in the descending motor command may also change the input at the spinal level, in addition to sensory feedback via the muscles spindles, thereby producing presynaptic inhibition of the Ia afferent signal which may also alter the discharge rate to the motor units (Baudry, Maerz, & Enoka, 2009; Gabriel, Kamen, & Frost, 2006; Manini et al., 2005).

Improvements in the ability to maintain steady and accurate force output may also be attributed to reductions in the coactivation of antagonist muscle (Enoka et al., 2003). For example, the activation of agonist and antagonist contractions could also produce fluctuations in the net resultant force (Enoka et al., 2003; Keen et al., 1994; Manini et al., 2005). Changes to coactivation as a result of resistance exercise training may be due to modifications or adjustments in the motor command to target muscles via modulation of intracortical inhibition (Duchateau et al., 2006; Zoghi, Pearce, & Nordstrom, 2003).

An additional mechanism that may also play a contributory role to the increased variability in motor output is altered presynaptic inhibition of the Ia afferents. Briefly, the excitatory input from the Ia afferent to motor neurons can be inhibited presynaptically by a regulated descending command, dampening the activation of motor units for the targeted muscle (Baudry et al., 2009; Baudry, Maerz, Gould, & Enoka, 2010; Kandel, Schwartz, & Jessell, 2000). Interestingly, depending on the task that is to be performed, be it position control or force control, older adults demonstrated a decreased ability to regulate presynaptic inhibition compared to young adults, which could account for the increased variability in the force output to the targeted muscle (Baudry et al., 2010). For example, Baudry and Enoka (2009) reported that the ability of older adults to regulate presynaptic Ia afferent inhibition was reduced when individuals where tasked to control a hand position while supporting (holding) a mass (position control) compared to exerting the same amount of force (force control) against a rigid constraint (Baudry et al., 2009).

Our proposed hypothesis that both groups would experience improved control of force output following 12 weeks of resistance training was evident in our findings. In addition, we further hypothesized that improvements in MFS or MFA, particular with eccentric contractions, may be greater with the eccentrically-biased RENEW intervention compared with TRAD, however, this was not evident in our findings. One limiting factor that may have influenced this outcome was that MFS and MFA testing were conducted in an open chain position using an isokinetic dynamometer, whereas the ECC loading during the 12 weeks of resistance exercise training was performed using a closed chain recumbent leg ergometer. Specific differences may have been detected if MFS and MFA were tested in a closed chain position. For example, one study was able to detect improvements in ECC coordination when performing closed chain resistive exercise training for 12 weeks and then tested individuals using a closed chain testing method (Mueller et al., 2009).

In general, our reported findings support the primary hypothesis of this present study, with the exception of the hypothesis of greater eccentric MFS and MFA improvements for RENEW. Resistance exercise training incorporated into a multicomponent exercise fall reduction program was effective in improving CON and ECC MFS, and ECC MFA in older fallers.

Conclusion

Resistance exercise training can reduce the variability in the force output exhibited by older adults who have experienced a fall. Improvements in MFS were attained during the performance of CON and ECC contractions following 12 weeks of resistance exercise training. However, improvements in MFA were observed only during ECC contractions following 12 weeks of resistance exercise training, partially correcting the tendency of participants to overshoot the target force. Participants were already accurate for MFA during CON contractions. There were no differential effects of the specific type of resistance exercise regimens (RENEW vs TRAD) with MFS or MFA.

Recruitment

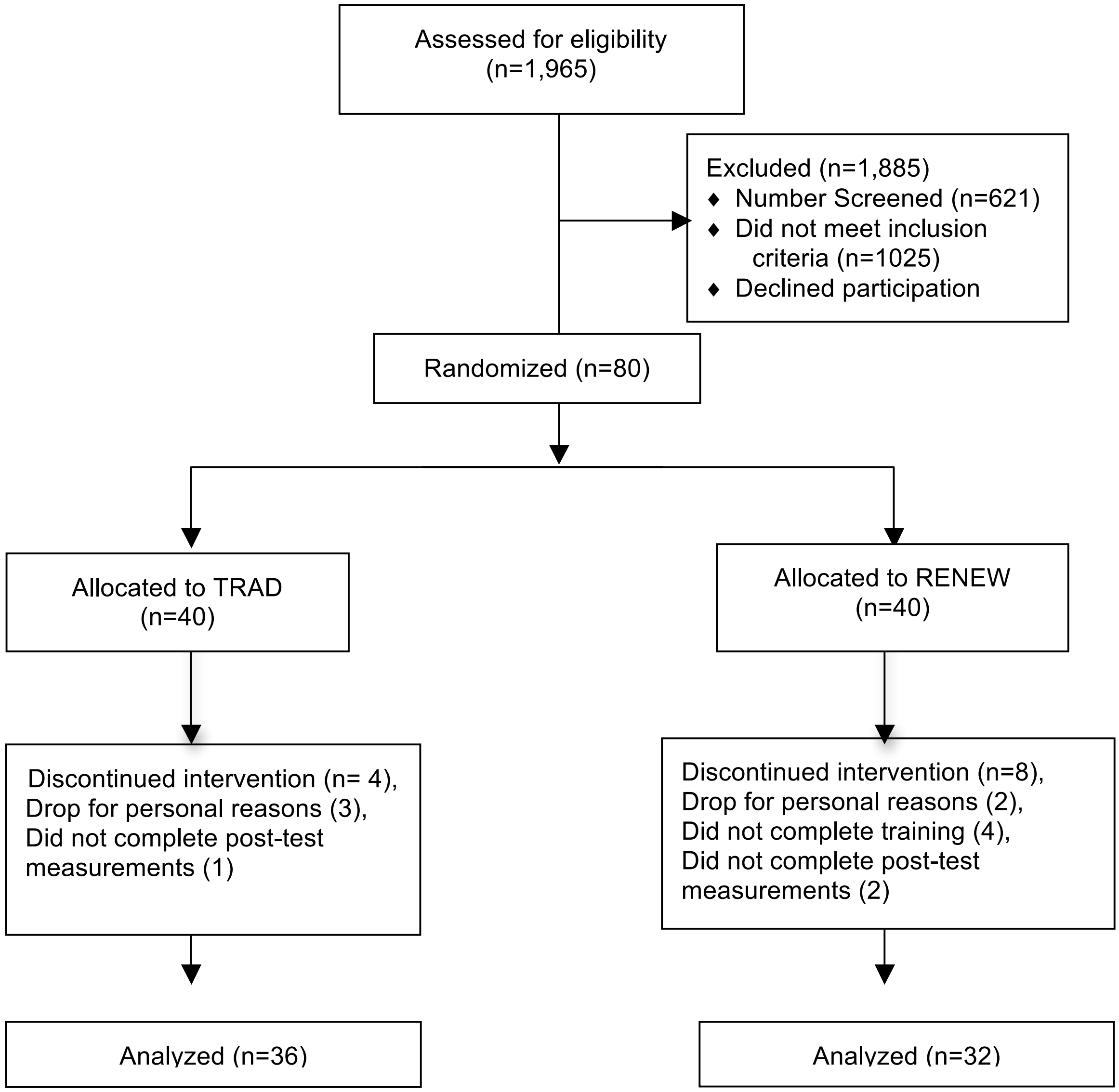
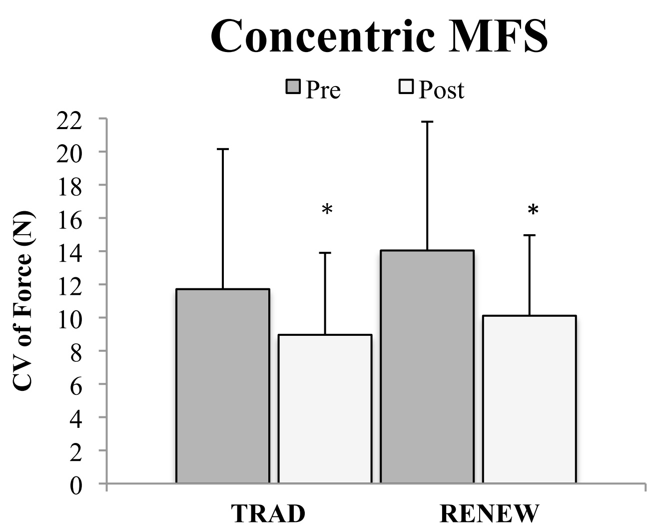


Figure 5.1 - Recruitment, randomization and participant allocation (consort)

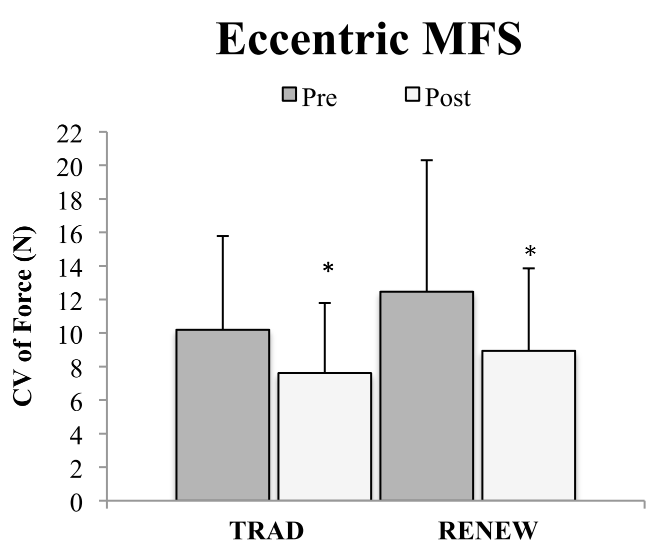
Figure 5.2 - Graphic illustration depicting eccentric ergometer used by the RENEW group. Participants resisted the alternating movement of the pedals towards them. The force exerted by the ergometer motor exceeds the force of the participant creating eccentric or negative work of the knee extensor muscles.

A)



* Significant, *P*<0.01

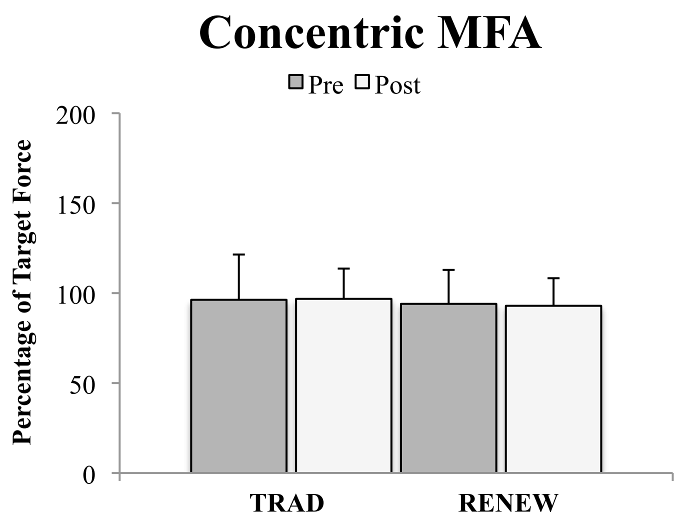
B)



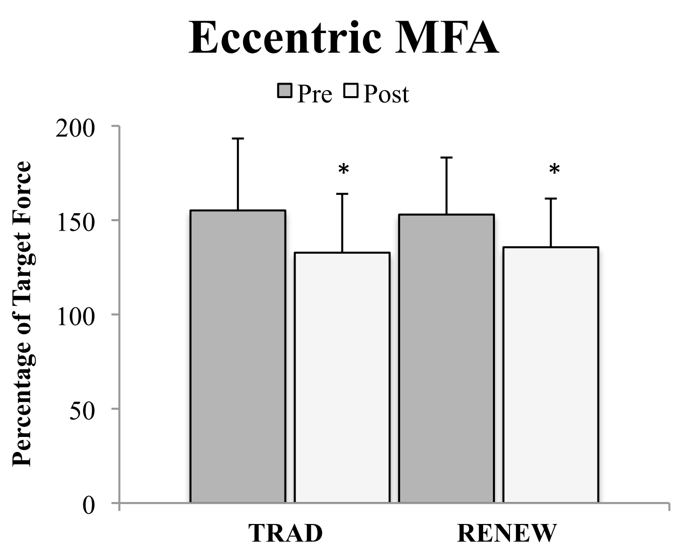
* Significant, *P*<0.01

Figure 5.3 - Muscle force steadiness for TRAD and RENEW groups pre- and post-12 weeks of training. Values represent means ± SD (error bar). A) The coefficient of variation of force (CV) during concentric contractions. B) The CV of force during eccentric contractions.

A)



B)



* Significant, *P*<0.01

Figure 5.4 – Muscle force accuracy (MFA) for TRAD and RENEW groups pre- and post-12 weeks of training. Values represent means ± SD (error bar). Muscle force accuracy was expressed as a percentage of the target force, [(mean force/target force) *100] where 100 is equivalent to matching the target force (N). Values above or below 100 represent force inaccuracy due to under or overshooting of the target force. A) The percentage of target force (%TF) accuracy during concentric contractions. B) The %TF accuracy during eccentric contractions.

Table 5.1 – Resistance exercise training schedule for traditional group

Training Week	Training Duration (sets & reps)	Lower Extremity Exercises
1	3x15	Leg Press Machine (60%-65% of 1RM) Standing 4 directional SLR (wt as tolerated)
3-12	3x15	Leg Press Machine (70% of 1 RM) Standing 4 directional SLR (wt as tolerated)

1 RM = 1 repetition maximum, SLR = straight leg raises

Table 5.2 – Eccentric resistance training schedule for RENEW group utilizing eccentric ergometer

Training Week	Training Duration (min)	Perceived Exertion
1	3-5	7 (very, very light)
2	5	9 (very light)
3	5-10	11 (fairly light)
4	10-12	11-13 (fairly light to somewhat hard)
5-12	12-15	11-13 (fairly light to somewhat hard)

Table 5.3 – Muscle force steadiness, expressed as the CV of force, pre- and posttraining

Groups	MFS (CV) Con Pre	MFS (CV) Con Post	MFS (CV) Ecc Pre	MFS (CV) Ecc Post
TRAD	11.71 ± 7.68	8.96 ± 3.99*	10.20 ± 4.35	7.61 ± 3.37*
RENEW	14.04 ± 6.73	10.11 ± 3.91*	12.47 ± 6.32	8.94 ± 4.47*

Values represent means ± SD, CV=Coefficient of Variation of Force
* Significant, $P<0.01$

Table 5.4 - Muscle force accuracy, expressed as a percentage of the target force, pre- and posttraining

Groups	**MFA (%TF) Con Pre**	**MFA (%TF) Con Post**	**MFA (%TF) Ecc Pre**	**MFA (%TF) Ecc Post**
TRAD	96.19 ± 25.18	96.83 ± 16.75	155.19 ± 38.16	132.81 ± 31.19*
RENEW	94.06 ± 18.88	92.94 ± 15.40	152.91 ± 30.27	135.56 ± 25.76*

Values represent means ± SD, MFA=Muscle force accuracy expressed as a percentage of the target force [(mean force/target force) *100] where 100 is equivalent to matching the target force. Values above or below 100 represent under or overshoot of the target force.
* Significant, P<0.01

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